Chapter 1

AN OVERVIEW
OF AQUIFER VULNERABILITY

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ABSTRACT

Aquifer vulnerability concerns assessment of risk associated with groundwater resources. Investigations are carried out based on concepts applied to assess groundwater bodies. Aquifer vulnerability concepts discussed are based on available input data (subjective, physical, and statistical); resource and source protection; intrinsic and specific approaches. The broad-based methods most vulnerability approaches follow are the hydrogeological and complex setting method, statistical method, mathematical method, parametric system method, and index method. Fifteen commonly used methods were reviewed, stating the concept, purposes, advantages, and limitations. The methods were selected based on applicability to karst topography, the basis for European vulnerability approaches, travel time concept based on physically based approaches and intrinsic vulnerability approaches. The review discusses the importance of vulnerability validation and suggests

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appropriate validation techniques that can be adopted. The review concludes with discussions on the challenges and directions for future contributions on aquifer vulnerability.

Keywords: aquifer vulnerability, risk assessment, resource protection, parametric system, RTt method, vulnerability validation

1. INTRODUCTION

Aquifer vulnerability assessments is a concept developed since the late sixties and early seventies (Margat, 1968; Albinet and Margat, 1970). Groundwater vulnerability definitions and classifications are broad, and different methods were developed for general and specific aims. Gogu and Dessargues (2000a), Magiera (2000), Goldscheider (2002), and Liggett and Talwar (2009) reviewed the various existing vulnerability methods. Statistical models, point count system models (PCSM), mathematical models, index model, and analogical model are some of the methods developed and used in vulnerability investigations. Vulnerability assessments are classified based on the scale (site, local, regional) or purpose (e.g., risk management, protection zoning) and to distinguish between source and resource vulnerability maps and specific and intrinsic vulnerability maps.

Based on the availability of input data of the hydrogeological system under consideration, three basic vulnerability methods can be adopted:

- Subjective methods.
- Physically based methods.
- Statistical methods.

The most popular of these methods is the subjective method. This is based on the rating of individual hydrogeological factors. The physically based method is an objective or process-based method widely used next to the subjective method. The physically based method relies on the physical processes that take place in the hydrogeological systems. The third approach, statistical methods, attempts predicting contaminant concentrations or probabilities of contamination based on correlations between aquifer properties and contaminant source and occurrence (Focazio et al., 2001; Hojberg et al., 2006; Sorichetta, 2010).

Two important issues that must be addressed before assessing groundwater vulnerability are:

- Groundwater assessment for the purpose of intrinsic or specific vulnerability.
- Selecting the target to be assessed.

Intrinsic vulnerability is susceptibility of groundwater to contaminants generated by human activities (Vias et al., 2006). Intrinsic vulnerability takes into account hydrogeological characteristics of an area, but is independent of the nature of the contaminant and the contamination scenario (Daly et al., 2002; Vias et al., 2006). Specific vulnerability takes into account the physicochemical properties of contaminants and their relationship to the physicochemical properties of the hydrogeological system. Specific vulnerability is useful when considering the aspect of land-use practises.

The target of groundwater vulnerability assessment can be either at the groundwater table (top of the aquifer in unconfined, confined, or leaky-confined conditions) or at the particular location in the saturated zone (Brouyère et al., 2001; Daly et al., 2002; Voigt et al., 2004). Based on the concept of target, groundwater vulnerability can further be grouped into two:

- The source protection vulnerability methods.
- The resources protection vulnerability methods.

For resource protection, groundwater surface is the target, and the pathway to the surface consists of vertical movement through the layers above the groundwater surface (Figure 1). For source protection, the water in the well or spring is the target, and the pathway includes mostly horizontal movement in the aquifer (Goldscheider et al., 2000). Although both are closely related to one another, it is, however, possible to protect source without protecting the resources.

1.1. The European Concept

The European approach to groundwater vulnerability assessments for protection of groundwater resources was based on two concepts:

- The protection of groundwater resources (target regional vulnerability assessment of overlying layers down to groundwater surface).
- The protection of groundwater sources (target well or spring including karst network) (Daly et al., 2002).

As contained in European Cooperation in the Field of Scientific and Technical (COST) research action 620 (2003), the concept of the European Approach should be broad-based and encompass all European conditions, but be sufficiently flexible to address the individual karstic regions it was designed for. The approach also suggests that the vulnerability methodologies should provide allowances for local conditions, information availability, time, and resources.

COST action 620 (2003) suggests that the concept of vulnerability mapping should be based on the origin-pathway-target model of environmental management (Daly et al., 2002). Origin is the term used to describe the location of a potential contaminant release. COST action 620 suggests taking the land surface as the origin. This refers to land use practices like cattle pasture and the spreading of pesticides. However, some contaminants are released below the ground surface, for example via leakages in sewerage systems and underground petrochemical tanks. The target (receptor) is the water to be protected. For resource protection, the target is the groundwater surface, and for source protection it is the water in the well or spring. The pathway includes everything between the origin and the target. For resource protection the pathway consists of the vertical passage within the protective cover, and for source protection it also includes horizontal flow in the aquifer (Figure 1). Different existing groundwater methodologies that use the European concepts will be discussed later.

1.2. Intrinsic Vulnerability

Assessing intrinsic vulnerability is like evaluating the protective capacity of cover layers to the introduction and transport of contaminants into the groundwater. Vulnerability assessment methods that use the intrinsic vulnerability concept including DRASTIC (depth-to-groundwater, net recharge, aquifer media, soil media, topography, impact of vadose zone, and hydraulic conductivity), AVI (Aquifer Vulnerability Index), and SINTACS (water table depth, effective infiltration, unsaturated zone, soil media, aquifer media, hydraulic conductivity and topographic slope) and are able to

distinguish degrees of vulnerability at regional scales where different lithologies exist (Vıas et al., 2005). However, these methods' weakness is that they are much less effective in assessing vulnerability in carbonate aquifers, as they do not take into account the peculiarities of karst. Vulnerability methods developed for addressing the karst environment are termed the European Approach. Examples of European vulnerability approaches include EPIK (epikarst development, protective cover, infiltration conditions and karst network development) by Doerfliger et al., (1999); Irish Approach (Daly and Drew, 1999); GOD (Foster, 1987; Robbins et al., 1998); COP (concentration of flow–overlying soils–precipitation) by Vias et al., (2006); and PI (protective cover and infiltration condition) by Goldscheider et al., (2000). Some of the European vulnerability approaches can also be applicable to nonkarst environments (e.g., PI, GOD, and SINTACS).

To evaluate intrinsic vulnerability, three basic points were noted by Daly et al., (2002). These basic points are:

- The advective travel time.
- The relative quantity of contaminants that reach the target, because not all contaminants that leave the surface catchment infiltrate into aquifer—some leave as surface run-off.
- The physical attenuation (dispersion, dilution, dual porosity effect).
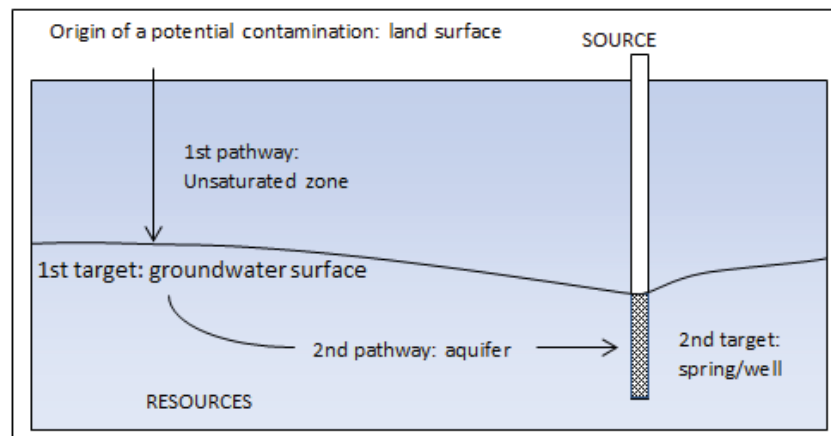
Source: Goldscheider et al., (2000).

Figure 1. Illustration of the origin-pathway-target model for groundwater vulnerability mapping and the concept of resource and source protection.

These points were highlighted in the European vulnerability approach (COST Action 620, 2003). Common intrinsic vulnerability methods are subjective (overlay or index) methods. The most common ones, as reviewed by Gogu et al., (2000a), are the following: Albinet and Margat (1970), Goossens and Van Damme (1987), Carter and Palmer (1987), GOD (Foster, 1987), DRASTIC (Aller et al., 1987), SINTACS (Civita, 1994), SEEPAGE (Moore and John, 1990), AVI (Van Stempvoort et al., 1993), ISIS (Civita and De Regibus 1995), EPIK (Doerfliger et al., 1999), and the German method (Von Hoyer and Söfner, 1998).

2. APPROACHES OF MAPPING GROUNDWATER VULNERABILITY

Different methods have been applied to mapping of groundwater vulnerability. These methods can be found in Vrba and Zaporozec (1994), COST Action 620 (2003), and Gogu and Dassargues (2000a). Five basic methods deducted by Goldscheider (2002) from the 69 vulnerability methods discussed by Magiera (2000) for mapping groundwater vulnerability are:

- Hydrogeological complex and setting methods.
- Index models and analogical relations.
- Parametric system models.
- Mathematical models.
- Statistical methods.

2.1. Hydrogeological Complex and Setting Method

The hydrogeological complex and setting (HCS) method was first used by Margat (1968) and Albinet and Margat (1970). This method is based on the assumption that two areas with comparable hydrogeological properties are characterised by similar groundwater vulnerability (Vrba and Zaporozec, 1994). The method is applicable to small-scale mapping (1:1 million). The HCS method takes into account the geological, hydrogeological, and topographical maps above the lithology (Goldscheider, 2002). The method was applied by Albinet and Margat (1970) to produce a vulnerability map of France. The German vulnerability map was prepared with the same HCS by

Vierhuf et al., (1981) using the same scale. The vulnerability was determined on the basis of the properties of the overlying layers and the depth of the groundwater table.

The major disadvantage of the HCS method is that validation is not possible; but HCS advantages include identifying different areas with significant different geological formations, such as a karst environment. Aller et al., (1987) further used the HCS concept to develop DRASTIC. However, the point count system model (PCSM) was used in assigning values to the DRASTIC index.

2.2. Mathematical Methods

There are a few examples of numerical methods used to assess groundwater vulnerability. Numerical methods are mostly applied separately to saturated and unsaturated zones and are frequently used in contaminant migration predictions. This makes the numerical methods relevant in water management protection zones (Goldscheider, 2002). Mageira (2000) describes nine examples for application of mathematical methods for specific vulnerability mapping on a large to medium scale. These models take into account both the properties of the contaminant (mostly nitrates and pesticides) and the properties of the overlying layers and are often verified. Numerical methods are rarely used in groundwater vulnerability assessment, even though they allow assessing and validating consistency of other vulnerability mapping methods (Daly et al., 2002).

The advantage of the mathematical methods is that they are easy to verify, since they are used in contaminant mapping. Neukum et al., (2008) presented a validation method based on simple numerical modelling and field investigations to validate qualitative vulnerability methods. Voigt et al., (2004) used mean travel time as a vulnerability indicator. Frind et al., (2006) applied a standard numerical flow and transport code to provide relative measures of intrinsic well vulnerability based on solute breakthrough curves. Neukum and Azzam (2009) presented a methodology comprised of four indicators to estimate vulnerability based on properties of solute breakthrough curves at the groundwater table. An index rating system was added to the efforts of Neukum and Azzam (2009) by Yu et al., (2010).

2.3. Statistical Methods

Due to the selective parameters evaluated out of the complex variables that should actually be assessed in most other vulnerability evaluations, the statistical and geostatistical methods provide alternative ways of evaluating large parameters. This has successfully been applied in small- to medium-scale mapping (Mageira, 2000; Panagopoulos et al., 2006; Sorichetta et al., 2010). The first step in a geostatistical vulnerability analysis is to map a selected number of influencing factors, such as depth-to-groundwater table, soil type, permeability, and recharge. The second step is to map spatial distribution of the concentration of a certain contaminant in the groundwater. The third step is to establish a correlation between the influencing factors and the contaminant concentration. This correlation can be used to map the specific vulnerability of groundwater to the selected contaminant (e.g., Teso et al., 1996). The major disadvantage of the geostatistical method is the difficulty in finding a correlation between contaminant concentrations and responsible influencing factors. It is also difficult to develop, and once established, can only be applied to regions that have environmental conditions similar to those of the region in which the statistical model was developed.

2.4. Parametric System Method

This is the most common approach in groundwater vulnerability mapping. Due to the wide usage of parametric methods, they have been subdivided into different approaches. Common among these approaches are the PCSMs that weight critical factors affecting vulnerability, matrix factors (MS), rating systems (RS), and sophisticated models of the processes occurring in the vadose zone (Lasserre et al., 1999; Connell and Daele, 2003; Babiker et al., 2005; Vías et al., 2005; Panagopoulos et al., 2006; Mende et al., 2007; Rahman, 2008; Saidi et al., 2011a).

The parametric system method involves selection of parameters assumed to be significant for vulnerability. Each parameter has a natural range which is subdivided into discrete intervals, and each interval is assigned a value reflecting the relative degree of sensitivity to contamination. The vulnerability of an area is determined by putting together the values of the different parameters using an MS, an RS, or a PCSM.

Examples of the parametric methods, usually named with an acronym formed from the factors that are taken into account, are DRASTIC (Aller et al.,

1987); EPIK (Doerfliger et al., 1999); SINTACS (Civital and De Maio, 2000); PI (Goldscheider et al., 2000) from the PCSM; and GOD (Foster, 1987) from the RS. DRASTIC is Depth-to-groundwater, net Recharge, Aquifer media, Soil media, Topography, Impact of vadose zone, and hydraulic Conductivity. GOD is Groundwater occurrence (e.g., none, confined, unconfined); Overlying lithology (e.g., alluvial, gravel, sandstone, limestone); and Depth-to-groundwater table. PI is Protective cover of the lithology above the water table and Infiltration condition at which the protective cover is bypassed. Full descriptions of some of these methods are presented in section 3 below.

2.5. Index Methods

Index methods and analogical relations follow standard descriptions of hydrological and geohydrological investigations based on a mathematical standard, for example transport equations (Magiera, 2000; Goldscheider, 2002). Most index methods are for the evaluations of specific vulnerability of groundwater to pesticides on a large to medium scale. The index method takes into consideration the overlying lithology and the contaminant. The attenuation factor introduced by Rao et al., (1985) is one of the earliest index methods used to map pesticides. Further work based on Rao et al., (1985) was the process-based indexed method used by Lowe et al., (2005) and incorporates physical and chemical processes through mathematical equations addressing the behaviour of certain chemicals in the subsurface.

3. REVIEW OF BASIC METHODS

A detailed description of some major and common vulnerability methodologies are given. The methods include intrinsic, European Approach, source, and resource vulnerability methods.

3.1. The PCOK Method

The PCOK conceptualised vulnerability method is based on the hazard-pathway-target model of the European concept (Daly et al., 2002). PCOK was designed by Daly et al., (2002) for the European Commission. The P represents precipitation—the total quantity, duration, and intensity of

precipitation that can influence the quantity and rate of infiltration. The four scenarios considered under the P factor are:

- Humid climate with extreme events.
- Humid climate without extreme events.
- Dry climate with extreme events.
- Dry climate without extreme events.

The C represents the flow concentration factor—the degree to which infiltration occurs. The C factor is dependent on many parameters which include:

- Presence of karst features or other places that concentrate infiltration flow.
- The parameters that control run-off, including slope, vegetation, and physical soil properties.

The O factor is the overlying layers between the land surface and the groundwater. Daly et al., (2002) identified four possible layer types according to previous work of Holting et al., (1996) and Goldscheider et al., (2000) for the O factor:

- Topsoil—weathering zones composed of minerals, organic substances, water, air, living matter, and roots.
- Subsoil—sediment of granular, unconsolidated material, such as sand, clay, and gravel.
- Nonkarst bedrock—nonkarstic rock like sandstone, schist, shale, and basalt.
- Unsaturated karstic bedrock, which includes epikarst.

Further parameters considered in the O factor reflecting the protective capacity of the overlying layers are:

- Important key data collected including layer thickness, hydraulic conductivity values, effective porosity values, macroporosity or fissuring, fracturing, or karstification.

- Other data that the main data can assess including grain-size distribution, lithological content, soil type, vegetation indicators, and drainage density.

The K factor is the main factor considering the karstic network of the saturated aquifer. The karstic source considered in these methods was both for the well and the spring (Figure 2). This means that the vertical and horizontal pathways through the saturated karstic bedrock must be considered. The K factor was lastly based on the COST Action 620 classification which in turn was based on a general description of the bedrock, giving a range of possibilities from porous carbonate-rock aquifers to highly karstified networks.
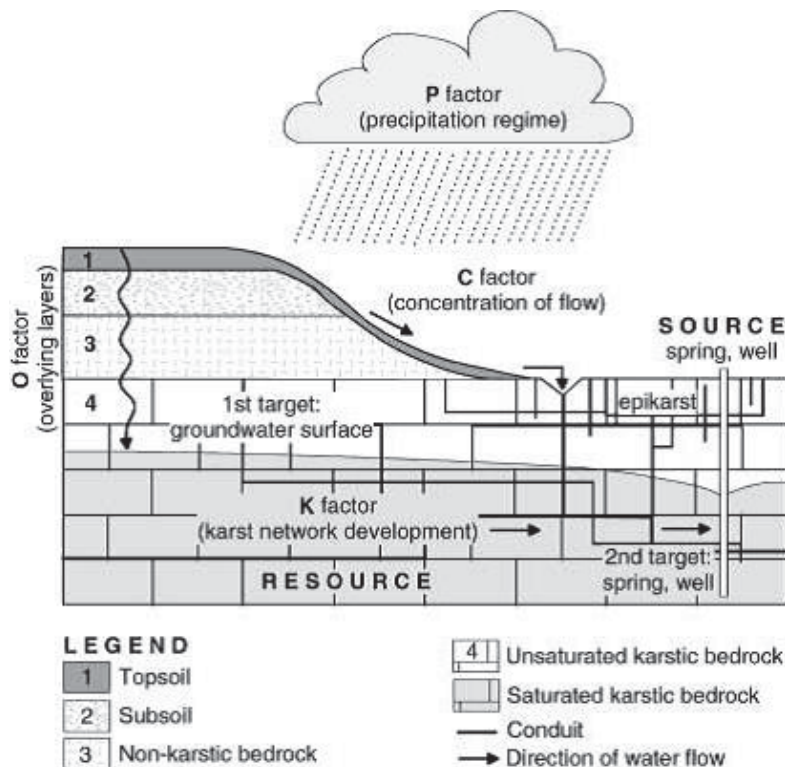
Source: Modified after Goldscheider et al., (2000).

Figure 2. Cross-section showing the PCOK method distribution of factors for intrinsic vulnerability maps.

3.2. The COP Method

The need to act on the recommendations of Daly et al., (2002), which failed to give guidelines, tables, or formulas for vulnerability assessment, propelled Vias et al., (2006) to propose the COP method following the European Approach and the factors highlighted in Daly et al., (2002). COP stands for Concentration of flow–Overlying soils–Precipitation. The COP method uses quantification and categorisation of parameters with the weighting of variables for the vulnerability index. This method is based on the concept of assessing the natural protection of groundwater.

The COP method follows the factor classifications of the PCOK parameters (Daly et al., 2002) with little modifications (Figure 3). The overlying layers are divided into soil subfactor [O_S] and lithology subfactor [O_L]. The COP method further subdivides the properties of rock responsible for its hydrogeological characteristics, including effective porosity and hydraulic conductivity, degree of fracturing [Iy], thickness of each layer [m], and confining conditions [cn]. An index is proposed similar to vertical protection (layer index), derived from the multiplication of thickness and lithology of each layer. This concept is based on the AVI and PI method by Van Stempvoort et al., (1993) and Goldscheider et al., (2000).

The C factor is a modifier of the Overlying factors [O]. The C factor is the degree to which precipitation at or near an aquifer outcrop is concentrated into the swallow hole, bypassing the unsaturated zone. The C factor concept in the COP method is based on the PI method of Goldscheider et al., (2000) and the EPIK method of Doerfliger and Zwahlen (1998). The C factor is further subdivided into two scenarios. Scenario 1 includes swallowed holes recharge areas considered under four variables:

- Distance to a swallow hole [*dh*].
- Slope and vegetation [*sv*].
- Distance to sinking stream [*ds*].
- No sinking stream is present.

Scenario 2 includes the rest of the area. This is also under two variables:

- Surface features [*sf*].
- Slope and vegetation [*sv*].
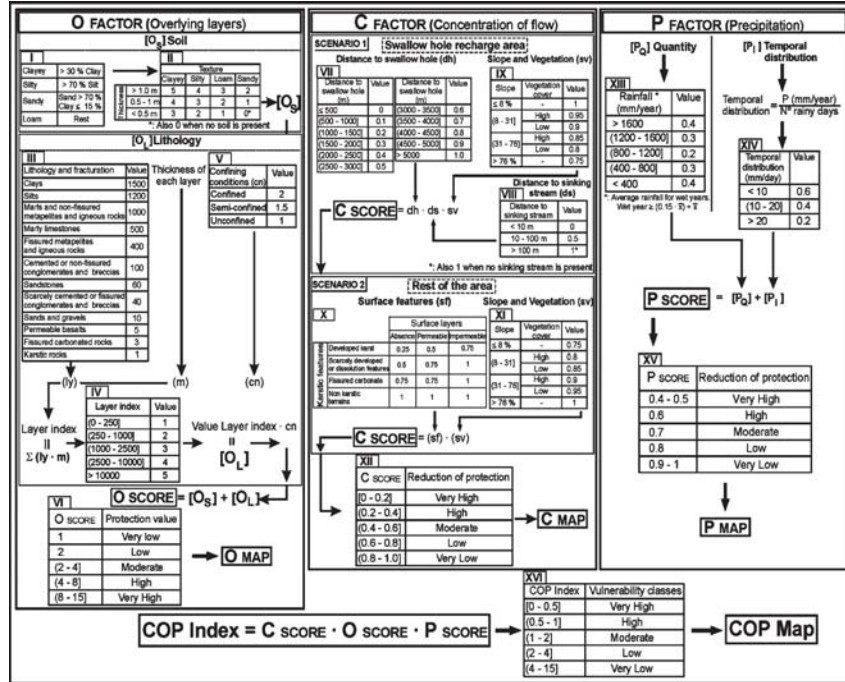
Source: Vias et al., (2006).

Figure 3. COP method, containing numeric evaluation and index.

Precipitation represents the P factor in the COP method. Precipitation as used in COP is the quantity of precipitation and the factors that influence the rate of infiltration, such as temporal distribution, duration and intensity of extreme rainfall events, and frequency. Two subfactors, quantity of precipitation [PQ] and temporal distribution of precipitation [PI], are used. COP precipitation is based on the assumptions that increase in precipitation up to 800–1,200 mm increases vulnerability, because transit time of contaminants infiltrating from the surface into groundwater is likely to be more important than the dilution process. The COP index range includes 0–0.5 as very high vulnerability, >0.5–1.0 as high vulnerability, >1.0–2.0 as moderate vulnerability, >2.0–4.0 as low vulnerability, and >4.0–5.0 as very low vulnerability (Figure 3).

The COP method was used to map the intrinsic vulnerability of two carbonate aquifers in southern Spain with differing climate, hydrogeology, and geology (Vias et al., 2006). Other areas where it was used are mapping the

karst terrains of South Africa (Leyland, 2008) and the application of modified COP+K in the Herrerias cave of Asturias, Spain (Marin et al., 2012; Andreo et al., 2009). The K factor is based on transit time, information on the karst network, and the degree of connection of it to the spring or well (Andreo et al., 2006).
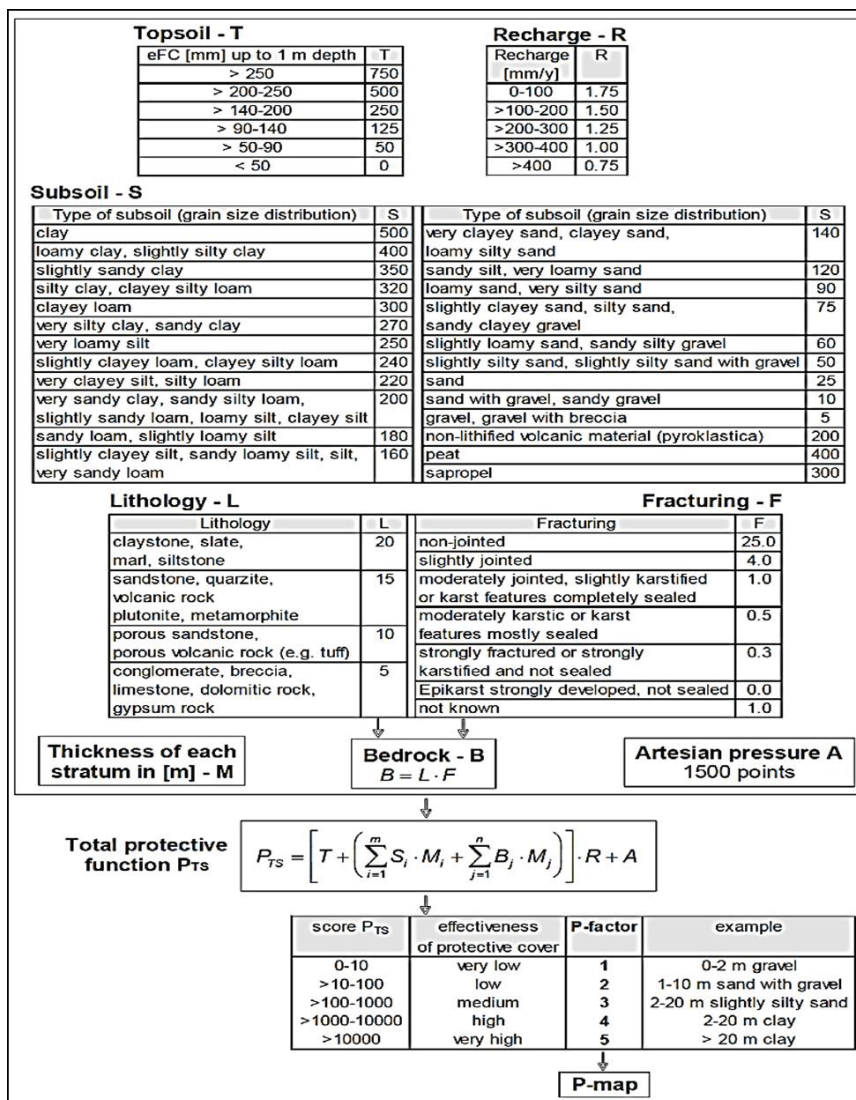
The advantage of the COP method is that it can be applied using available geo-environmental data, but with some fieldwork. COP can also be used without the extensive input of a geographic information system (GIS) common to most vulnerability methodologies. In summary, the overlying layers [O] of the COP method were basically derived by multiplying the thickness and the lithology of each layer. This is the same as the simplified AVI method by Van Stempvoort et al., (1993). If a simpler method could effectively summarise the overlying lithology of COP and PCOK, there is no need for going through the longer route.

3.3. The PI Method

The PI method developed by Goldscheider et al., (2000) marked a further advance in assessing the degree of vulnerability of karst aquifers. The PI method applies the concept of pollutant transport from an origin on the surface (i.e., above the soil) through the pathway of the unsaturated zone to the groundwater surface. The P factor is applicable to all types of aquifers and is based on an assessment scheme initially proposed by Hölting et al., (1995), while the I factor accounts for karst specific recharge and infiltration processes.

The P factor describes effectiveness of the protective cover resulting mainly from the thickness and hydraulic properties of all the strata between the ground surface and the groundwater table (Figure 4), the soil, the subsoil, the nonkarstic bedrock, and the unsaturated zone of the karstic bedrock (Goldscheider, 2002). The I factor describes infiltration conditions, particularly the degree to which the protective cover is bypassed as a result of lateral surface and subsurface flow (Tables 1 and 2). Therefore, the I factor distinguishes between the dominant flow processes (infiltration, subsurface flow, or surface flow).

The final protection factor π is the product of P and I. It is subdivided into five classes (Table 3). A protective factor of $\pi \leq 1$ indicates a very low degree of protection and an extreme vulnerability to contamination; $\pi = 5$ indicates a high degree of protection and a very low vulnerability.

Topsoil - T

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

Recharge - R

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

Subsoil - S

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

Lithology - L

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

Fracturing - F

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

Thickness of each stratum in [m] - M

Bedrock - B
$$B = L \cdot F$$

Artesian pressure A
1500 points

Total protective function P_{TS}

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

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

P-map

Source: Goldscheider et al., 2000.

Figure 4. Determination of P factor in the PI method.

Table 1. Step determination of dominant I flow

First step: Determination of the dominant process				
		Depth to low permeability layer		
		<30 cm	30–100 cm	>100 cm
Saturated hydraulic conductivity (m/s)	$>10^{-4}$	Type D	Type C	Type A
	$>10^{-5}$–10^{-4}		Type B	
	$>10^{-6}$–10^{-5}	Type E		
	$\leq 10^{-6}$	Type F		
Second step: Determination of I factor				
Forest				
Dominant flow process		<3.5%	3.5–27.0%	>27.0%
Infiltration	Type A	1.0	1.0	1.0
Subsurface flow	Type B	1.0	0.8	0.6
	Type C	1.0	0.6	0.6
Surface flow	Type D	0.8	0.6	0.4
	Type E	1.0	0.6	0.4
	Type F	0.8	0.4	0.2
Field/meadow/pasture				
Dominant flow process		<3.5%	3.5–27.0%	>27.0%
Infiltration	Type A	1.0	1.0	0.8
Subsurface flow	Type B	1.0	0.6	0.4
	Type C	1.0	0.4	0.2
Surface flow	Type D	0.6	0.4	0.2
	Type E	0.8	0.4	0.2
	Type F	0.6	0.2	0.0

Table 2. Step determination of I factor

Third step: Determination of the I factor							
Surface catchment map		I factor					
		0.0	0.2	0.4	0.6	0.8	1.0
A	Swallow hole, sinking, and 10 m buffer	0.0	0.0	0.0	0.0	0.0	0.0
B	100 m buffer on both sides of sinking stream	0.0	0.2	0.4	0.6	0.8	1.0
C	Catchment of sinking stream	0.2	0.4	0.6	0.8	1.0	1.0
D	Area discharging inside karst area	0.4	0.6	0.8	1.0	1.0	1.0
E	Area discharge out of the karst area	1.0	1.0	1.0	1.0	1.0	1.0

Table 3. Index of vulnerability map derived from P factor and I factor

Vulnerability map Vulnerability of groundwater		P map Protection function of overlying layers		I map Degree of bypassing		
Description	Π factor	Description	P factor	Description	I factor	
Extreme	>0–1	Very low	1	Very high	0-0.2	Red
High	>1–2	Low	2	High	0.4	Orange
Moderate	>2–3	Moderate	3	Moderate	0.6	Yellow
Low	>3–4	High	4	Low	0.8	Green
Very low	>4–5	Very high	5	Very low	1.0	Blue

The following characteristics of karst systems are relevant in respect to groundwater vulnerability and should consequently be taken into account (Goldscheider, 2005):

- Each karst system has its individual characteristics; generalisation is problematic.
- Karst systems are heterogeneous and anisotropic; interpolation of data is thus difficult and the reliability of a vulnerability map can be lower for karst than for other areas.
- There is both diffuse and point recharge. Adjacent nonkarst areas may generate surface flow that may enter the karst aquifer via swallow holes (allogenic recharge).
- The epikarst, if present, controls the infiltration into the aquifer. It may store water and concentrate flow. The structure and function of epikarst is often difficult to assess.
- Karst aquifers may comprise conduits, fissures, and intergranular pores. Contaminants can be transported very fast in the conduits or stored in the fissures and pores (matrix).
- Karst systems portray strong hydraulic and physicochemical reactions to hydrological events.
- The water table and hydraulic gradient are often difficult to define, particularly in shallow and conduit systems.
- Karst catchments are often large and hydraulically connected over long distances. Karst catchments may overlap and the flow paths (proved by tracer tests) may cross each other.

There are limitations to the PI method. The protective cover factor takes into account the total annual recharge dependent on annual precipitation, and the infiltration conditions factor takes into consideration the predominant flow process. This depends on the properties of the area and the precipitation regime, namely the time distribution of precipitation. This may not be possible to calculate for data-limited areas due to the high numbers of calculated parameters.

The classification of dominant flow processes (I factor) is not exactly certain. Although it follows a stepwise procedure, its classification does not leave room for a possible flow process outside the listed range. Also, the saturated hydraulic conductivity values only range between $>10^{-4}$ and $<10^{-6}$. Values outside this range are also difficult to place within the stated documented values.

For the protective function of the PI method, Daly et al., (2000) suggest modification of the overlying layers on the basis of the protective property multiplied by thickness (m), and they suggest permeability as a means to evaluate the protective properties (see also Goldscheider, 2002). They further recommend using grain size distribution (GSD) and protective properties of subsoil material, which the GLA method (Holting et al., 1996) has linked with permeability and provided standard values for. This indirectly means that the P factors of the PI method can be reassessed by simply determining the GSD and multiplying it by the thickness. Therefore, for simplification and usage in data-lacking areas, protective cover as used in the PI method can be evaluated using standard values as presented in Kunoth (2000), multiplied by lithology thickness.

3.4. The EPIK Method

The EPIK method developed by Doerfliger et al., (1999) takes four factors into account: epikarst development (E), protective cover (P), infiltration conditions (I), and karst network development (K). Each factor is given a ranking index, and a weighting coefficient is attributed to each of the indexed factors according to their degree of protection. The epikarst (E) is a subsurface, a highly fissured and karstified zone, which can extend between decimetres and tens of metres. Its main functions are water storage and flow concentration. The degrees of epikarst development are assessed based on geomorphological karst features. Three classes are distinguished:

E_1 Swallow holes, dolines, karrenfields.
E_2 Intermediate zones between the aligned dolines, dry valleys.
E_3 The rest of the catchment.

The protective cover *(P)* includes the soil and other nonkarstic formations overlying the karst aquifer. Four categories are defined:

P_1 0–20 cm of soil and/or low-permeability formations.
P_2 >20–100 cm of soil and/or low-permeability formations.
P_3 More than 1 m of soil and/or low-permeability formations.
P_4 More than 8 m of low-permeability formations, or more than 1 m of soil on 6 m of low-permeability formations.

The infiltration *(I)* takes into consideration the type of recharge into the karst aquifer. Areas with diffuse infiltration are considered less vulnerable than areas that drain by concentrated recharge via a swallow hole. Four classes are distinguished:

I_1 Perennial or temporary swallow holes and sinking streams, including the beds and banks of the streams, as well as artificially drained sectors within the catchment of these streams.
I_2 Naturally drained areas inside the catchments of swallow holes or sinking streams with steep slopes (more than 10% for arable areas, more than 25% for meadows and pastures).
I_3 Areas inside the catchment of swallow holes or sinking streams with gentle slopes (less than 10% or 25%, respectively); low lying areas outside such a catchment that collect run-off, and steep slopes that generate this run-off.
I_4 Rest of the area.

The karst network development (K) is classified in the following ways:

K_1 A moderate to well-developed karst network with conduits decimetres to metres wide.
K_2 A poorly developed or blocked karst network.
K_3 Fissured nonkarstic limestone aquifers and systems that infiltrate in porous media.

Table 4. Rating used to calculate EPIK protection index

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

Table 5. EPIK vulnerability and protection index

Vulnerability	Protection factor	Protection
Very high	$F < 19$	S1 (source protection zone
High	$19 < F < 25$	S2 (inner protection zone)
Moderate	$F > 25$	S3 (outer protection zone)
Low	$F > 25, P = P_4, I = I_{3,4}$	Rest of the catchment

Calculation of the EPIK rating protection index and vulnerability index is shown in Tables 4 and 5, respectively. The protection index F is calculated with the formula:

$$F = 3E + P + 3I + 2K \qquad \text{Equation 1}$$

There are limitations to the EPIK method. A major disadvantage of EPIK is that it can only be used in karst areas. Other shortcomings of the EPIK method, as discussed by Goldscheider (2002), include:

- Important parameters such as recharge and thickness were omitted.
- Epikarst (E) was based on the geomorphology of the karst, which is unreliable.
- Weighting system was contradictory.
- 0 was missing, making 1 the minimum value of each attribute, even if its effect on protection was 0.
- The EPIK formula was not always applicable and not defined for all hydrogeological settings.

3.5. The Slovene Approach

The Slovene Approach is thus far the most complete interpretation of the European Approach (Ravbar, 2007; Ravbar and Goldscheider, 2007). It can be used for vulnerability mapping and includes an assessment of contamination hazards, an evaluation of the importance or value of the groundwater, and

different types of risk maps. The Slovene Approach was developed for source and resource vulnerability mapping, since it is built on the PI method. It is complete, realistic, and direct. The Slovene Approach is based on the framework of the COP method (Figures 5 and 6) and partly based on the PI method (Vias et al., 2006; Andreo et al., 2006). The complete parameters involved in the assessment of the Slovene Approach are shown in Table 6.
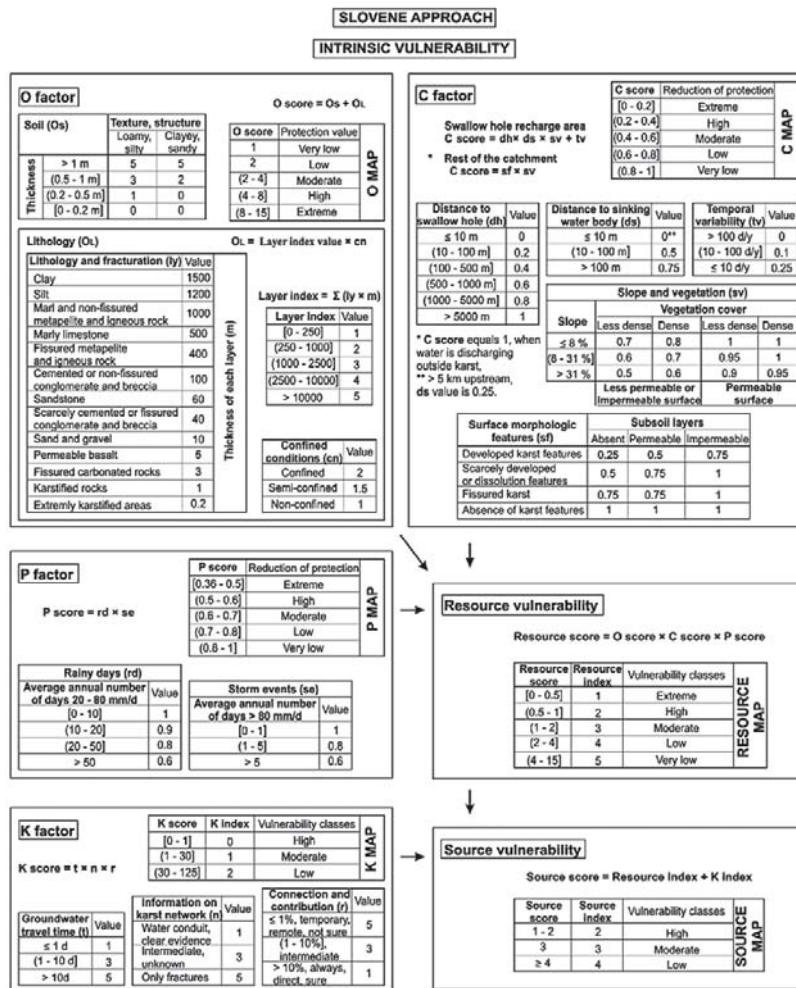
Source: Ravbar and Goldscheider (2007).

Figure 5. Slovene Approach source and resources intrinsic vulnerability evaluation.

Table 6. Factors and data required for the four selected vulnerability methods in mapping Slovene karst catchment

Methods	Factors	EPIK	Simplified method	PI	Slovene Approach
Karst unsaturated zone	Top soil thickness	+	+	+	+
	Top soil texture	−	−	+	+
	Top soil structure	−	−	+	+
	Subsoil permeability	+	+	+	+
	Subsoil thickness	+	+	+	+
	Depth of the unsaturated zone	−	−	+	+
	Fracturing	−	−	+	+
	Epikarst development/ geomorphological features	+	−	+	+
	Confined situation	−	−	+	+
Recharge conditions	Concentration of flows	+	+	+	+
	Slope gradient	+	−	+	+
	Land use/vegetation cover	+	−	+	+
	Autogenic recharge	+	+	+	+
	Allogenic recharge	+	+	+	+
	Temporary variability	-	-	-	+
Karst saturated zone	Presence of active karst network	+	-	-	+
	Hydrological characteristics of a source	+	-	-	+
	Tracer test interpretation	+	-	-	+
Resource vulnerability		−	+	+	+
Source vulnerability		+	−	−	+

Source: Ravbar and Goldscheider (2009).

3.6. The DRASTIC Method

The DRASTIC empirical method was developed by Aller et al., (1987) to evaluate the pollution potential of groundwater systems on a regional scale. The method is the most widely used groundwater vulnerability method for mapping a wide range of contaminants (Fritch et al., 2000; Piscopo, 2001; Al-Adamat et al., 2003; Thirumalaivasan et al., 2003; Lobo-Ferreira and Oliveira, 2003; Ramos-Leal and Rodriguez-Castillo, 2003; Murat et al., 2004; Vias et

al., 2005; Herlinger and Viero, 2006; Stigter et al., 2006; and Rahman, 2008). DRASTIC has been widely modified to suit specific investigations (Akhavan et al., 2011; Shirazi et al., 2013). The DRASTIC index is calculated roughly analogous to the likelihood that contaminants released from the surface will reach the groundwater.

The primary purpose of DRASTIC is to provide assistance in resource allocation and prioritisation of many types of groundwater-related activities and to provide a practical educational tool. DRASTIC can be used to set priorities for areas to conduct groundwater monitoring. For example, a denser monitoring system might be installed in areas where aquifer vulnerability is higher and land use suggests a potential source of pollution. DRASTIC can also be used with other information (such as land use, potential sources of contamination, and beneficial uses of the aquifer) to identify areas where special attention or protection efforts are warranted.

No.	Hazards	Classification criteria	Ranking factor (Qn)				
			0.8	0.9	1	1.1	1.2
1.	**Infrastructural development**						
1.1.	Waste water (urbanisation)	Population density (inhabitant/km²)	< 10	[10 - 50]	[50 - 100]	[100 - 500]	≥ 500
1.2.	Waste disposal (unprotected/illegal)	Volume (1000 m³)	< 0.1	[0.1 - 1)	[1 - 5)	[5 - 10)	≥ 10
1.3.	Fuels	No. Pumps	< 2	[2 - 5)	[5 - 10)	[10 - 15)	≥ 15
		Amount of storage (t)	< 0.5	[0.5 - 1)	[1 - 5)	[5 - 10)	≥ 10
1.4.	Transport and traffic, roads	No. Vehicles/day	< 100	[100 - 1,000)	[1,000 - 5,000)	[5,000 - 10,000)	≥ 10,000
	Railway	No. Trains/day	< 10	[10 - 25)	[25 - 50)	[50 - 100)	≥ 100
1.5.	Recreational facilities	No. Visitors/day	< 10	[10 - 100)	[100 - 500)	[500 - 1,000)	≥ 1,000
1.6.1.	Graveyard	Size (1000 m²)	< 5	[5 - 10)	[10 - 50)	[50 - 100)	≥ 100
1.6.5.	Military installations and dereliction	Size (km²)	< 1	[1 - 5)	[5 - 10)	[10 - 25)	≥ 25
2.	**Industrial activities**						
2.1.	Mining (in operation and abandoned)	Volume (1000 m³)	< 0.1	[0.1 - 1)	[1 - 5)	[5 - 10)	≥ 10
2.2.	Excavation sites	Volume (1000 m³)	< 0.1	[0.1 - 1)	[1 - 5)	[5 - 10)	≥ 10
2.4.	Industrial plants (none mining)	Water consumption (1000 m³/year)	< 1	[1 - 5)	[5 - 10)	[10 - 50)	≥ 50
2.5.	Power plants (wind turbines)	Power (kw)	< 50	[50 - 100)	[100 - 500)	[500 - 1,000)	≥ 1,000
2.6.	Industrial storage	Volume (1000 m³)	< 0.1	[0.1 - 1)	[1 - 5)	[5 - 10)	≥ 10
2.7.	Diverting and treatment of waste water	Capacity in PU (Person unit)	< 500	[500 - 1,000)	[1,000 - 1,500)	[1,500 - 2,000)	≥ 2,000
3.	**Livestock and agriculture**						
3.1.	Livestock	Livestock in LU (Livestock unit)	< 5	[5 - 10)	[10 - 50)	[50 - 100)	≥ 100
		Livestock density (LU/ha cultivated land)	< 0.5	[0.5 - 1)	[1 - 1.5)	[1.5 - 2)	≥ 2
3.2.	Agriculture	Livestock in LU (Livestock unit)	< 5	[5 - 10)	[10 - 50)	[50 - 100)	≥ 100
		Livestock density (LU/ha cultivated land)	< 0.5	[0.5 - 1)	[1 - 1.5)	[1.5 - 2)	≥ 2
		Annual consumption of manure or liquid manure (m³/ha cultivated land)	< 1	[1 - 5)	[5 - 10)	[10 - 15)	≥ 15
		Annual consumption of mineral fertilizers (kg/ha cultivated land)	< 1	[1 - 10)	[10 - 50)	[50 - 100)	≥ 100
		Annual consumption of pesticides (kg/ha cultivated land)	< 1	[1 - 5)	[5 - 10)	[10 - 50)	≥ 50

Source: Ravbar and Goldscheider (2007).

Figure 6. Ranking factors of selected hazards used in the Slovene Approach.

The model has four assumptions:

- The contaminant is introduced at ground surface.
- The contaminant is flushed into groundwater by precipitation.
- The contaminant has the mobility of water.
- The area being evaluated by DRASTIC is 100 acres or larger.

DRASTIC was not designed to deal with pollutants introduced in the shallow or deep subsurface by methods such as leaking underground storage tanks, animal waste lagoons, or injection wells. The methodology is not designed to replace on-site investigations or to site any type of facility or practice. For example, DRASTIC does not reflect the suitability of a site for waste disposal. Although DRASTIC may be one of many criteria used in siting decisions, it should not be the sole criterion.

DRASTIC was established based on the Delphi technique (Aller et al., 1987). To assess the level of risk this technique utilises the practical and research experiences of professionals in the area of interest. DRASTIC was divided into four categories through the rating system: low, moderate, high, and very high. The higher the DRASTIC rating, the greater the prospect of aquifer contamination.

DRASTIC considers seven hydrogeological factors: (1) Depth-to-water; (2) net Recharge; (3) Aquifer media; (4) Soil media; (5) Topography (slope); (6) Impact of the vadose zone media; and (7) hydraulic Conductivity of the aquifer.

Each of the hydrogeological factors is assigned a rating of 1 to 10 based on a range of values. The ratings are then multiplied by a relative weight ranging from 1 to 5. The most significant factors have a weight of 5; the least significant have a weight of 1. The ranges and ratings for each hydrogeological factor are listed in Table 7, and the following formula shows an addition to the DRASTIC method:

$$\text{DRASTIC Index} = D_R D_W + R_R R_W + A_R A_W + S_R S_W + T_R T_W + I_R I_W + C_R C_W \qquad \text{Equation 2}$$

where:
D, R, A, S, T, I, and C are the seven parameters of the model
subscripts R and W are the corresponding ratings and weights, respectively

DRASTIC applications are probably the best known and widely used methods of vulnerability mapping. DRASTIC applications include mapping contaminant and groundwater protection.

DRASTIC has been widely modified to suit different problems. Modifications include addition of land use conditions, sewage, pesticides and other agricultural contaminants. The DRASTIC model was used for vulnerability assessment in Portugal by using hydrogeological parameters, and the final map of the DRASTIC model was developed in ARC/INFO GIS software on a 1:500 scale (Lobo-Ferreira and Oliveira, 1997). Groundwater pollution vulnerability using DRASTIC/GIS was carried out in Midnapur, West Bengal. The DRASTIC index for both generic and industrial municipal and pesticide pollutants was derived, and vulnerability maps were prepared for both (Shahid, 2000).

Recent studies have used DRASTIC in a fuzzy logic-based environment for pesticide modelling to account for uncertainty (Chen and Kao, 1997; Dixon et al., 2002). Fuzzy rule-based models provide comparable results with less input data, as well as improved vulnerability prediction when DRASTIC factors are used (Dixon, 2001, 2004, 2005). Incorporation of fuzzy rules and neural network (NN) with DRASTIC variables improved vulnerability prediction for pesticides.

Several drawbacks of the DRASTIC method include:

- It is not based on a clear conceptual model such as the origin-pathway-target model.
- Several of the factors are redundant, such as the factors A and C, because hydraulic conductivity is directly dependent on the aquifer medium.
- DRASTIC is not a multidimensional approach. The one-dimensional approach of this method might be sufficient to assess the vulnerability of a typical alluvial aquifer where water and contaminant percolate vertically from the land surface down to groundwater, but not so for karst areas where water and contaminant bypass protective function through lateral flow into swallow holes.
- DRASTIC overemphasizes slopes.
- DRASTIC index score intervals do not readily allow for continuous data.
- Maps are difficult to update.

Table 7. Assigned weights for DRASTIC hydrogeological factors

Rating	Depth of water (m) D × 5	Net recharge (mm/y) R × 4	Aquifer media A × 3	Soil media S × 2	Topography T x 1	Impact of vadose zone I × 5	Hydraulic conductivity (GPD/ft^2) C × 3
10	0–1.5		Karst limestone	Thin or absent, gravel	0–2	Karst limestone	<2,000
9	>1.5–4.5	>250	Basalt	Sandstone & volcanic	2–3	Basalt	
8		180–250	Sand & gravel	peat	3–4	Sand & gravel	1,000–2,000
7	>4.5–9.0		Massive sandstone & limestone	Shrinking and/or aggregate clay/alluvium	4–5	Gravel, sand	
6		100–180	Bedded sandstone & limestone	Sandy loam, schist, sand, karst volcanic	5–6	Limestone, gravel, sand, clay	700–1,000
5	>9–15		Glacial	Loam	6–10	Sandy silt	
4			Weathered metamorphic/igneous	Silty loam	10–12	Metamorphic gravel & sandstone	300–700
3	>15–23	50–100	Metamorphic/igneous	Clay loam	12–16	Shale, silt, & clay	
2	>23–31		Massive shale	Muck acid, granitoid	16–18	Silty clay	100–300
1	>31	0–50		Nonshrink & nonaggregated clay	>18	Confining layer, granite	1–100

Source: Al-Hanbali and Kondoh (2008).

3.7. The AVI Method

Another method of aquifer vulnerability assessment is the Aquifer Vulnerability Index (AVI) of Van Stempvoort et al., (1993). This method was approved by the Canadian Prairie Provinces Water Board. AVI's methodological strength relies on vadose zone characterisation, which has been noted as being the most important single parameter in aquifer vulnerability evaluation (McLay et al., 2001; Herbst et al., 2005). It can be directly related to the physical properties of the vadose zone (Ross et al., 2004). AVI computes aquifer vulnerability on the basis of hydraulic resistance (c) as a ratio between the thickness of each sedimentary unit above the

uppermost aquifer (d) and the estimated hydraulic conductivity of each of these layers (*K*). Hydraulic resistance is calculated by:

$$c = \sum_{i=1}^{n} \frac{d_i}{K_i}$$

<div align="right">Equation 3</div>

where:
   n = number of sedimentary units above the aquifer
   d_i = thickness of the vadose zone
   K_i = hydraulic conductivity of each protective layer
   K = unit of length/time (m/s or m/d)
   c = travel time with dimension in seconds

Hydraulic resistance c (vulnerability index) is an inverse indicator of vulnerability. This is vertical flow of water through the protective layers. This can be used as a rough estimate of vertical travel time of water through the unsaturated layers. It is important to note that significant parameters controlling the travel time like hydraulic gradient and diffusion are not considered in AVI. This is one of the major limitations of the AVI method. Other limitations include:

- The AVI method is not regarded as a complete vulnerability method.
- The c is hydraulic resistance of fluid and not the only factor resisting fluid movements.
- The method is too simplified.

Even if there are a lot of methodologies that consider the processes occurring in the vadose zone more accurately, the AVI method is one of the best (Lasserre et al., 1999; Connell and Daele, 2003). The AVI index is perhaps most suitable at a large regional-scale vulnerability assessment (Zwahlen, 2004).

3.8. The PaPRIKA Method

This method is designed for resource and source vulnerability assessment based on EPIK, PI, RISK, and COP. PaPRIKA factors in the functional and structural conditions of an aquifer. P means protection, which includes soil cover, unsaturated zone, and epikarst aquifer behaviour. R represents the rock

type, I stands for infiltration, and KA is the karstification factor (Doerfliger, 1994; Doerfliger et al., 2010). PaPRIKA allows for additional factors such as groundwater travel time and the active conduit network on the vulnerability map. Significant with PaPRIKA are soil characteristics (texture, structure, and thickness); nonsaturated zone (thickness, lithology, and fracture degree); and epikarst aquifer, all factored into the protective cover assessment. The degree of fracturing of the aquifer body along with lithology accounts for the R factor, while slope with karst accounts for the infiltration factor. Chemical variability was added to karst degree with spring discharge, as well as velocity rates, indicated by artificial tracing techniques. PaPRIKA's major disadvantage is that recharge is not considered, and larger factor space is given to karstic terrains.

3.9. The SINTACS Method

The SINTACS method, proposed by Civita in 1994 and many times enhanced until the fifth remodification (Civita and De Maio, 2000) is partially derived from DRASTIC. It uses the same seven parameters, but is more flexible as to ratings (R) and weights (W). It provides five weight classifications: normal impact, severe impact, drainage (by streams), karst (aquifers), and fissured (aquifers). The SINTACS index (or contamination potential) is a sum of the rating of each of the seven parameters multiplied by the associated weight. SINTACS method limitations include:

- SINTACS assumed rating and weight to parameters like the DRASTIC method.
- Selected parameters are not the only important parameter affecting aquifer vulnerability.

3.10. The GOD Method

This vulnerability method was proposed by Foster (1987). GOD takes into account the type of groundwater occurrence (G) (e.g., none, confined, unconfined); overlying lithology (O) (e.g., loam, gravel, sandstone, limestone); and depth of the groundwater table (D). GOD is rated between 0 and 1. Overall value for vulnerability assessment is derived by multiplying the three factors, which consequently ranges between 0.0 (negligible) and 1.0 (extreme).

The main advantage of the GOD method is that it can be applied to any type of aquifer, except in the karst areas. The special nature of epikarst and vertical shaft is another problem when using this method in a karst environment. Other shortcomings include overrating of the factor D—for example, a depth of 100 m to the water table is assigned as moderate vulnerability (0.4).

Other methodologies developed for vulnerability assessment incorporate sophisticated tools such as neuro-fuzzy techniques (Dixon, 2005a) or the fuzzy quantification approach combined with the Ordered Weighted Average procedure (Gemitzi et al., 2006). A simplified approach to vulnerability was used by Nguyet and Goldscheider (2006). This approach was first applied to the tropical karst area in Vietnam. A similar simplified approach applied to data-limited environments (Ravbar and Goldscheider, 2007) considered the importance of groundwater source and resource, particularly of the Slovene Approach. The simplified approach and Slovene Approach characterised and delineated the site investigated using lithological, geomorphological mapping, geophysical survey, structural and tracer testing to evaluate the karst aquifers.

Brouyere et al., (2001) suggest that three practical questions a vulnerability assessment has to answer are the following:

- If pollution occurs, when will it reach the target?
- At which concentration level?
- For how long will the target be polluted?

It is suggested to use a so-called "vulnerability cube." The three axes of the cube are the transfer time, the maximum concentration, and the duration of a contamination. Vulnerability mapping should be based on assessing all the intrinsic properties that control the impulse response of the system to a DIRAC-type input of a conservative contaminant.

Frind et al., (2006) applied a standard numerical flow and transport code to provide relative measures of intrinsic well vulnerability based on solute breakthrough curves. Neukum and Azzam (2009) presented a methodology comprised of four indicators to estimate vulnerability based on properties of solute breakthrough curves at the groundwater table. A modification of the above method is presented by Yu et al., (2010), providing an index system for vulnerability assessment.

4. TRAVEL TIME CONCEPT
IN VULNERABILITY PATHWAYS

Vulnerability pathways are the summation of layers between the ground surface and the water body, particularly the water table, in resource vulnerability assessment. Source vulnerability assessment can also be from the groundwater surface through the unsaturated and saturated layers below the ground to a drinking well. Pathways in vulnerability assessment are important in determining flow characteristics and flow alterations of percolating fluids. Pathway assessments are physically based, and not much work has been done on vulnerability pathways, compared to other subjective vulnerability methods.

The travel time concept in vulnerability assessment has used different terminologies in the literature. Transit time, turnover time, residence times, and seepage time are some of these terminologies, based on contaminant movement or time of fluid. Timescale in vulnerability studies is important because it provides a basis for design of physically based groundwater vulnerability indices. According to Focazio et al., (2001), physically based methods take into account the physical process of flow and transport and do not have to rely on deterministic simulations. Physically based (process-based, objective) methods were initially seen as requiring "analytical or numerical solutions to mathematical equations that represent processes governing contaminant transport" (NRC, 1993). Disadvantages are managing large data, problems with upscaling and downscaling of results and difficulties with representation of preferential flow.

Vulnerability assessment by travel time consideration was recommended by Fried (1987) for the second phase of elaboration of hydrogeological maps of groundwater resources in the European Community. Travel time was already used by some countries to produce the vulnerability map of Valence, France (BRGM, 1979); in the Netherlands (Meinardi, 1982); in Denmark (Villumsen et al., 1982); and in the United Kingdom (The British Geological Survey since 1984). These maps were produced with residence time in the unsaturated zone based on the assumption that the contaminant and the physical properties are not different from that of water.

Four vulnerability categories were proposed based on the above travel time concept in the maps: greater than 20 years; one to 20 years; one week to one year; and less than one week. Based on the methodologies of the above mentioned groundwater vulnerability maps, Anderson and Gosk (1987)

considered their applicability and discussed whether vulnerability could be quantified as depending on the travel time of pollutants to the aquifer. They stated that the travel time of a pollutant from the source to the aquifer plays an important role in vulnerability mapping and can be used as a vulnerability indicator only for situations where removal of the pollutant is dependent on time.

A simplified methodology for estimation of vertical and horizontal travel and flushing timescales with nitrate threshold concentrations in Irish aquifers was presented by Fenton et al., (2011). The concept was based on time lag of contamination (nutrient literally) transport from source to receptor via hydrological and hydrogeological pathways. Horizontal travel time was estimated for first occurrence of nutrients in a surface water body with the piston-flow model under steady state conditions. The authors ascertain that an appraisal of catchment time lag issues offers a more realistic scientifically based timescale for expected water quality improvements in response to mitigation measures implemented under the WFD (2010).

The particle-tracking model for contaminant travel time in pathways was used by Eberts et al., (2012) and Sousa et al., (2013). In Eberts et al., (2012), particle tracking was compared to lumped parameters and was used for evaluating vulnerability of production wells to contamination. Selected characteristics of breakthrough curves from the particle tracking and lumped-parameter models for each investigated well were compared to determine which, if any, of the model differences notably affect contaminant predictions.

According to Witczak et al., (2007), time lag for vertical transport of conservative contaminants from the surface to a shallow aquifer can be a basis for vulnerability classification. These time lags were calculated as either ratios of exchangeable water content in the unsaturated zone to recharge flux (typically natural infiltration) or from conductivity and active porosity of soil layers above the saturated zone of the aquifer.

In karst areas, transit time was developed for physically based lateral flow within the uppermost weathered zone (epikarst) and high velocities of vertical infiltration at discrete infiltration points (e.g., sinkholes) or lines (e.g., dry valleys, faults) (Brosig et al., 2008). The transient time method considers lateral water flow along the slope within the epikarst towards final infiltration points in dry valleys/wadis. The method takes into account the assumption that surface water run-off within karst catchment areas only occurs during or shortly after storm events. As preferential flow occurs in a sink horst, infiltrating water is assumed to flow almost immediately into the epikarst compartment with sink holes as the end point. By applying this method, the

travel time of water is calculated by the ratio of travel path length between the infiltration point and the corresponding dry valley and the average pore water velocity.

Residence time of groundwater in an aquifer is another travel time concept. The residence times of groundwater in the upper aquifer were evaluated based on the WEKU model (Kunkel and Wendland, 1997), which in turn is based on the Darcy equation. Residence times determined for unconsolidated rock areas typically ranged between 10 and 25 years, whereas residence times <5 years were assessed for consolidated rock areas. The residence times of percolate water in soil were derived from the water storage capacity of soils (field capacity) and the percolate water rate (Herrmann et al., 2012).

Hydrochemical data has been used extensively in estimating vulnerability. The use of hydrochemical data was first proposed by Bachmat and Collin (1987). They expressed vulnerability by only one factor, as the anticipated change in concentration of a given substance in the groundwater per unit efflux of the mass of the substance at the ground surface. They argued that the resulting change of pollutant concentration is a function of travel time of the substance from the ground surface to the groundwater. The travel time through the unsaturated zone is a function of the thickness of the unsaturated zone (composed of a sequence of lithological, differentiable, homogeneous layers) and the average downward velocity of the pollutant (similar to the AVI method of Van Stempvoort et al., 1993).

Three models were later suggested by Bachmat and Collin (1987). These models were aimed at velocity of the pollutant depending on levels of complexity:

- The piston-flow model, which assumes that the pollution moves at the average velocity of the water, i.e., velocity is equal to the vertical specific discharge of the water divided by the effective moisture content of the layer.
- The advection-dispersion model (Bear, 1979), which assumes that the pollutant is advected at the average velocity of the water and dispersed owing to the fluctuation of the velocities of the individual water particles.
- The pollutant-specific velocity model, where the pollutant moves with its own velocity, which may differ from that of the carrier (Gvirtzman et al., 1986).

4.1. Established Travel Time Formulas
in Vulnerability Assessment

There are a few commonly used formulas for estimating travel time in groundwater vulnerability assessment. A technique to assess unsaturated and saturated zone time lag in the travel time from ground surface to receptor was proposed by Sousa et al., (2013). They described a series of techniques for estimating travel time in unsaturated and saturated zones using the advective travel time concept. In the saturated zone, particle-tracking techniques and straight-line approximation based on Darcy's equation were proposed. For the unsaturated zone, three techniques were proposed to calculate the saturated term $S(z)$:

- Applying the Van Genuchten equation, while assuming no flow conditions in the unsaturated zone.
- One-dimension variable saturated modelling.
- Tabulated values from surface to aquifer advective time (SAAT) and vulnerability techniques developed by Province of Ontario (2006) into the general formula:

$$tu = \int_0^L \frac{nef(z) \cdot S(z)}{R} dz \qquad \text{Equation 4}$$

where:

tu = the travel time in the unsaturated zone

L = the thickness of the unsaturated zone, which can be estimated using data from the observation well

R = the recharge

n_{ef} = the effective porosity estimated from the field or from literature

S = water saturation

Sousa et al., (2013) applied these methods to a field site in a glacial aquifer system in Ontario, Canada. These methods are useful to decide whether to incorporate unsaturated processes in conceptual and numerical models and can be used to roughly estimate the total travel time between points near ground surface and a groundwater receptor.

One-dimensional transient time (steady-state flow, transient transport) was created especially for quantitative intrinsic vulnerability assessment in the

VULK model for karst settings (Sinreich et al., 2007; Zwahlen, 2004). The concept of dominant transit time (maximum concentration = C_{max}) and attenuation (inverse of relative maximum concentration C_0/C_{ma} where C_0 is input concentration) used as VULK key output parameters (Figure 7) representing the three proposed criteria for assessing vulnerability includes:

- When should the pollution start?
- To which level?
- For how long?

An assessment of intrinsic vulnerability of conservative contaminants was attempted by Saayman et al., (2007). They based their study on evaluation of vertical travel time from land surface to the aquifer. They proposed calculating travel time using a simple formula:

$$T_{time} = \frac{Z \cdot \theta}{V_d}$$
<div align="right">Equation 5</div>

where:

T_{time} = travel time (years)
Z = vadose zone depth (m)
θ = average moisture content or volumetric water content
V_d = average recharge rate (m/day)
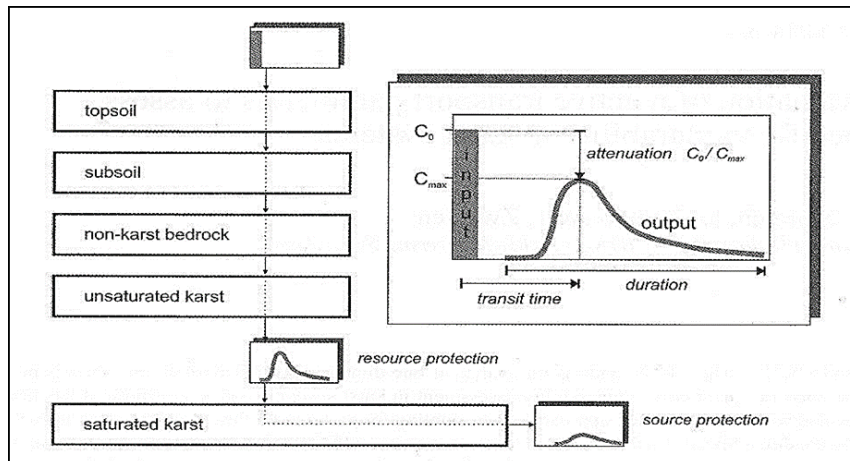
Figure 7. The VULK model source and resource vulnerability idea.

Witkowski and Kowalczyk (2004) also used this equation to assess groundwater vulnerability of conservative contaminants in Poland. Saayman et al., (2007) applied their findings to two study sites in South Africa: the Goedehoop irrigation site near Secunda and the Coastal Park waste disposal site near Cape Town.

Three models for calculating travel time of contaminant were presented by Krogulec (2004). Migration time was based on the time of water exchange in a rock formation assuming piston flow. The first model was of infiltration time through the unsaturated zone as proposed by Wosten et al., (1986); Haith and Laden (1986); and Witczak and Zurek (2002).

$$t_a = \sum_{i=1}^{n} \frac{m_i \cdot (w_o)}{I_e} \qquad \text{Equation 6}$$

where:

　　m_i = thickness of successive layers of unsaturated zone profile [m]

　　t_a = travel time through the vadose zones

　　w_0 = average volumetric moisture of successive layers of unsaturated zone

　　I_e = infiltration of atmospheric precipitation deep into the soil profile [$m^3/m^2 \times$ year] obtained through multiplication of infiltration rate (ω_i [%]) by volume of precipitation

The second model was based on volumetric moisture content of sediments to calculate infiltration time. The second model can be calculated according to Bindeman's formula:

$$t_a = \sum_{i=1}^{n} \frac{m_i \, n_o}{\sqrt[3]{I_e^2 K'}} \qquad \text{Equation 7}$$

where:

　　n_0 = effective porosity

　　K = vertical hydraulic conductivity of unsaturated zone

The rest of the parameters (m_i, I_e, t_a) are the same as for the first model.

The Bindeman equation states that infiltration time, excluding thickness of the unsaturated zone which is taken into account in all formulas, primarily depends on infiltration intensity and effective porosity, but is of lesser importance in the infiltration coefficient.

The third model presented to evaluate infiltration time was the formula proposed by Macioszczyk (1992). The model modified the earlier formulas:

$$t_a = \sum_{i=1}^{n} \frac{m_i\, w_o}{\sqrt[3]{I_e^2 K'}}$$

Equation 8

Seepage time was used to estimate the vulnerability of vadose layers at a carbonate aquifer in Cracow, Poland. Seepage time was based on Bindeman's simple formula and calculated using the Witczak and Zurek (2002) modified formula:

$$t = \frac{1000wm}{W}$$

Equation 9

where:
t = seepage time (year)
w = rock moisture volume
m = thickness of isolation cover (m)
W = infiltration intensity (mm/year)

Time of vertical seepage through the lithological strata covering the rocks was calculated with the formula and modified in order to adapt to the multilayer profile as follows:

$$t_v = [(m_1 w_1) + (m_2 w_2) + (m_3 w_3) + m_4 w_4) + (m_5 w_5)] * 1000/W$$

Equation 10

where:
t_v = time of vertical seepage to the phreatic zone (years)
W = infiltration intensity of atmospheric precipitation (mm/year)
m_{1-5} = thickness of succeeding lithological layers
w_{1-5} = rock moisture volume

Five classes were distinguished based on this vertical seepage through the vadose zone:

- Very high – seepage time less than two years.
- High – seepage time of two to five years.
- Medium – seepage time from 5 to 25 years.
- Low – seepage time from 25 to 100 years.
- Very low – seepage time more than 100 years.
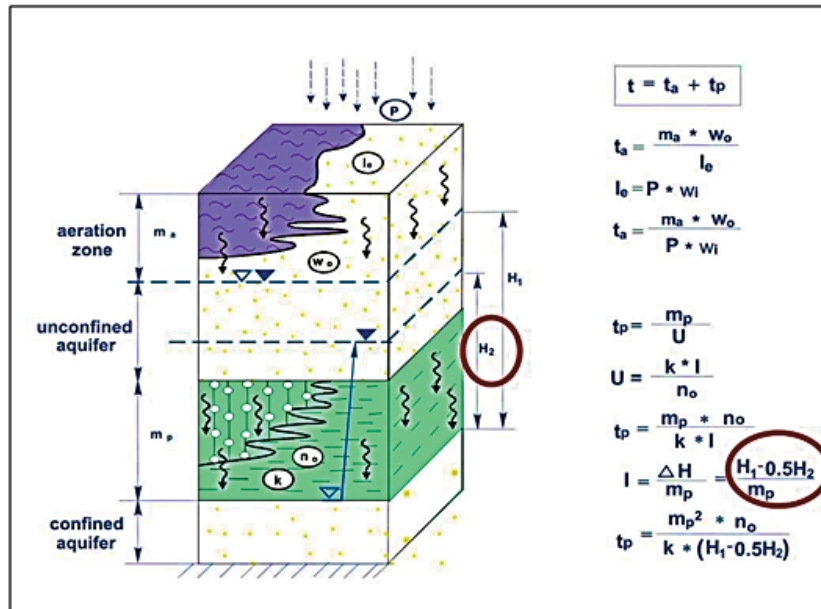
Source: Witczak et al., (2004); Kleczkowski et al., (1990).

Figure 8. Major groundwater basins vulnerability assessment.

Kleczkowski et al., (1990) attempted vulnerability mapping on countrywide major groundwater basins (MGWB) based on qualitative and quantitative criteria. These criteria include:

- The presence of at least one well having a yield greater than 70 m^3/h.
- Total groundwater abstraction of one intake greater than 10,000 m^3/d.
- Transmissivity greater than 10 m^2/h.
- Good water quality (Witczak et al., 2007, 2010).

Travel time of contaminant was depicted through the recharge area (Figures 8 and 9). Intrinsic vulnerability was based on vertical surface to aquifer and horizontal transport time of the contaminant to the borders of MGWB using the piston-flow model (Witczak et al., 2011). Intrinsic vulnerability of the MGWBs and their recharge areas was classified as follows:

- High vulnerability – with travel time shorter than five years, requiring extreme protection and maximum protection areas (MPA).
- Moderate vulnerability – with travel time of 5–25 years, requiring high protection and high protection areas (HPA).
- Low and very low vulnerability – with travel time longer than 25 years, requiring usual protection and standard protection areas (SPA).
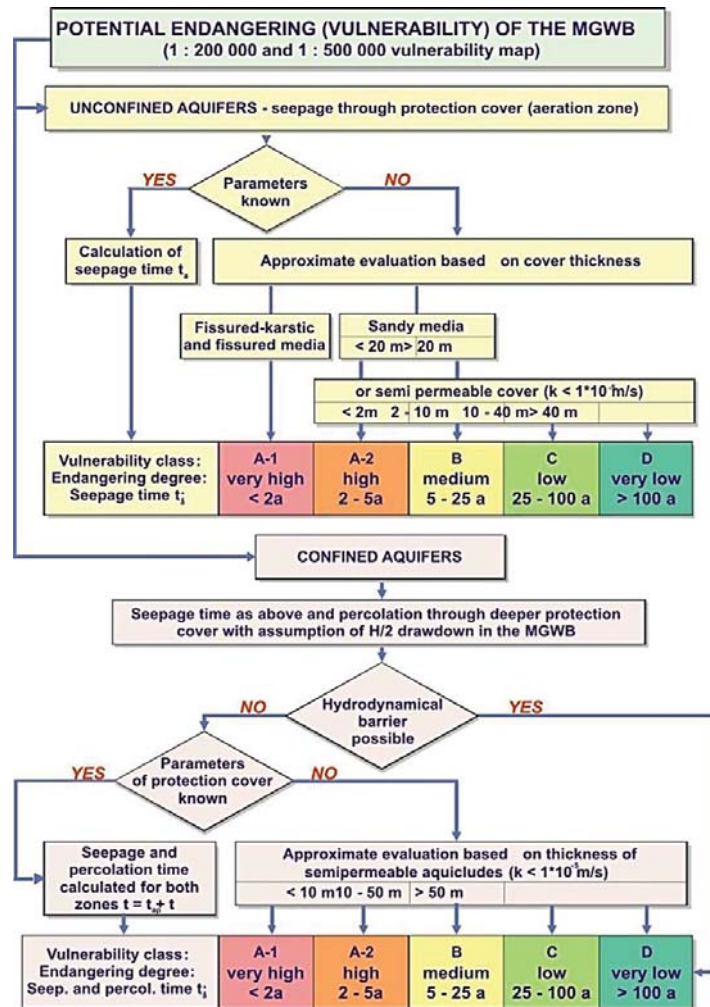
Source: Witczak et al., (2004); Kleczkowski et al., (1990).

Figure 9. Major groundwater basins' vulnerability assessment.

A simplified advective travel time of rainfall to shallow groundwater was proposed in the RTt vulnerability method developed by Oke (2015). Travel time was indirectly calculated based on important parameters affecting flows in unsaturated zones. These include depth to water table, soil property, hydraulic conductivity, and porosity. Travel time formula is then calculated based on a modified Darcy's equation as follows:

$$Tt = \sum_{i=1}^{n} \frac{D*S}{\left(\frac{K_{sat}}{\theta}\right)} \qquad \text{Equation 11}$$

where:

Tt = travel time
D = depth from ground surface to aquifer (m)
K_{sat} = hydraulic conductivity at saturation of successive layers (m/s)
Θ = effective porosity of the medium
S = slope (elevation head difference: dh/dl) in meters
N = numbers of layers between ground surface and the top of the aquifers

The final intrinsic vulnerability was computed by rating rainfall and travel time as follows:

$$RTt = R_R R_w + Tt_R Tt_W \qquad \text{Equation 12}$$

where:

R_R = rainfall rating = 10
R_w = rainfall weight
Tt_R = travel time rating = 10
Tt_W = travel time weight

The RTt method is designed for a data scarce area to assess groundwater vulnerability to contamination. RTt was applied to assess the shallow aquifers of the Dahomey Basin of Nigeria (Oke et al., 2016b), and the result was compared to other vulnerability methods used in assessing the vulnerability of the same basin (Oke and Vermeulen, 2016a).

5. VALIDATION OF VULNERABILITY METHODS

Scientists have not agreed on a specific method to validate aquifer vulnerability assessments. Vulnerability assessors have used different convenience techniques to validate proposed vulnerability methods. Commonly used validation methods, as highlighted by Daly et al., (2002), Gogu et al., (2003), and Neukum et al., (2008), include hydrographs, chemographs, bacteriological analyses, tracer techniques, water balances, calibrated numerical simulations, and analogue studies. Nguyet and Goldscheider (2006, 2007) and Oke (2015) in their studies used bacteriology applications in validating the outcome of their vulnerability studies. Artificial tracers were applied by Jeannin et al., (2001) as additional techniques for the validation of vulnerability maps.

Goldscheider et al., (2001) proposed three criteria: peak time, recovery (R), and maximum concentration normalised by the injected tracer mass *(c/M)*, all obtained from tracers' breakthrough curves. Ravbar and Goldscheider (2009) also used lithium chloride (LiCl) and potassium iodide (KI) released over the surface of limestone beds and partly covered by vegetation as tracers to validate four vulnerability methods. They proposed two validation criteria based on Perrin et al., (2004) and Andreo et al., (2006): the time of the first tracer detection and normalised tracer recovery R_N. This criterion is defined as:

$$R_N = \frac{1}{M} \int_{i=0}^{\infty} c \, dt = \frac{R}{Q} \qquad \text{Equation 13}$$

where:

R_N = normalised tracer recovery
R = recovery
Q = spring discharge
c/M = injected tracer mass
R = directly proportional to the spring discharge Q

Neukum et al., (2008) discussed the inappropriateness of qualitative methods of vulnerability assessment and presented a validation methodology based on simple numerical modelling and field investigations. The fuzzy vulnerability approaches combining ordered weighted average procedures by Gemitzi et al., (2006) and neuro-fuzzy techniques by Dixon (2005) were validated by comparing the results with water quality data, trying to form a sensitivity analysis.

Rahman (2008) employed a single-parameter sensitivity analysis and map-removal sensitivity analysis. Map removal involves removing one or more data layers and observing the variation in vulnerability. He noted that net recharge shows the highest sensitivity upon removal in the groundwater vulnerability index for DRASTIC. This is because of the mean variation index and high theoretical weight assigned to net recharge parameters. Other parameters' sensitivity orders were removal of topography, hydraulic conductivity, soil media, and aquifer median (Saidi et al., 2011b).

Single-parameter sensitivity involves comparing theoretical weights with effective weight of a vulnerability map. This was also used by Babiker et al., (2005). The effective weight of DRASTIC was reported to exhibit some deviation from that of the theoretical weight, and the effective weight is a function of the value of the single parameter with regards to the other six parameters. Rahman (2008) reported net recharge and depth-to-water layers as the most effective parameters in the vulnerability assessment of DRASTIC models. This was followed by hydraulic conductivity and topography, respectively, with other parameters such as aquifer media, soil media, and impact of vadose zone showing lower effective weight.

Ramos-Leal and Castillo (2003) presented the aquifer vulnerability validation study for the Turbio River Valley in Mexico using effective weighting Wxvi (Napolitano and Fabbri, 1996; Gogu and Dassargues, 2000b):

$$Wxi = \frac{XriXwi}{Vi} * 100 \qquad \text{Equation 14}$$

where:

Xri and Xwi are the ranges and the assigned weights for each parameter X, and Vi is the vulnerability index of each point

Ramos-Leal and Castillo (2003) went even further and proposed another validation method, namely vulnerability variation Vvxi by Lodwick et al., (1990), derived by parameter omission:

$$Vvxi = \frac{Vi-Vxi}{Vi} * 100 \qquad \text{Equation 15}$$

where:

Vvxi = variation index omitting a parameter X (D, R, A, S, T, I, or C).
Vi = vulnerability index in the point i.

Vxi = vulnerability index calculated without a parameter, X (D, R, A, S, T, I, C).

The two formulas are different but equivalent.

6. CHALLENGES AND EXPECTED FUTURE CONTRIBUTIONS TO VULNERABILITY ASSESSMENT

The most commonly accepted subjective vulnerability method is the DRASTIC method. Despite DRASTIC being well known and the most widely used method merely because of its simplicity, it has continuously been subjected to criticism. One of the major reasons for this criticism is the subjectivity DRASTIC introduced and the oversimplification in the hydrogeological characterisation. However, data gathering in computation of DRASTIC parameters is challenging in data-limited areas. Opinions differ about the DRASTIC method. In fact, some authors such as Barber et al., (1993) and Merchant (1994) argued that an equivalent DRASTIC result might be obtained using fewer parameters, with several advantages in accuracy, precision, and costs (Napolitano and Fabbri, 1996).

Travel time or transit time concepts were used more in the physically based vulnerability methods, which were mainly for steady state conditions. Environmental tracers involving arrival time serve as some of the yardsticks in measuring travel time. Numerical modelling simulating field conditions were used to arrive at travel time in some methods. However, laboratory simulation options have not been fully utilised. Even though laboratory factors in overall vulnerability assessment may be task specific and site specific, numerical modelling is another avenue to explore in vulnerability assessment.

It is permissible to ignore short travel time of very shallow aquifers (Basu et al., 2012; Eberts et al., 2012) in vulnerability studies. Short travel time makes no difference between the source and receptor and is better assumed under saturated conditions. Sousa et al., (2013) further support this assumption if travel time is negligible in the overall pathway travel time.

Likewise, disagreement over the concept of precipitation as to increase or decrease in groundwater vulnerability is important to state. Methods such as PI and DRASTIC maintained that a decrease in groundwater vulnerability occurs when increasing precipitation infiltrates into groundwater. The methods' argument was that an increase in recharge provides higher dilution and

consequently decreased vulnerability. The SINTACS method by Civita (1994) specifically proposes reduction in vulnerability if recharge is higher than 300–400 mm/year, while DRASTIC proposes values >250 mm/year. This means more recharge means more dilution and decreased vulnerability. However, the COP argument is more tenable in this study, because it relates travel time of contaminant with vulnerability. COP maintains the importance of quantity to dilution. Precipitation of 800–1,200 mm increases vulnerability, because more precipitation will be available to recharge the groundwater. In addition, the upside of precipitation inclusion in vulnerability methodology is that most methods accept rainfall quantity and annual recharge as interrelated and an important factor in assessing groundwater vulnerability.

The challenges of using most of these established vulnerability methods is that they were designed to include most factors influencing vulnerability and sometimes duplicate key intrinsic parameters. This allows for capturing all possible avenues by which contaminants infiltrate from the ground surface to the water table. However, satisfying these conditions may become a daunting task for data-limited areas. Data gathering for vulnerability assessment in data-limited areas can be economically expensive and labour intensive; and there is a shortage of qualified geohydrologists, particularly in developing economies. Therefore, there is a need for a simplified vulnerability method that can address data-limited areas. Although the RTt method was designed to address these shortfalls, there is room for improvement.

Another area of challenge using all established vulnerability methods discussed in this review, particularly the subjective methods, is the lack of physical precision of most methods. This is the disadvantage of most of the established subjective methods, because in reality the heterogeneity of most lithologies can create a wide gap between predicted map and actual field occurrence. This is despite the validation of most methods, which is why no two vulnerability methods give the same results when applied to assess an area. It is therefore suggested that for future uses, if possible, separate vulnerability methods factoring in *in situ* properties should be designed for every area intended to be assessed.

For intrinsic vulnerability mapping, it is important to take into account in the vulnerability methodology inherent properties of the areas under investigation. Since these properties are quite large and cannot all be factored into vulnerability methods, it is best to use a methodology that will factor in inherent parameters through which groundwater is contaminated. One of these methods is the travel time concept, which relates directly or indirectly to parameters through which water or contaminant flows. However, one major

challenge of intrinsic vulnerability methodologies is not considering the specific properties of contaminants.
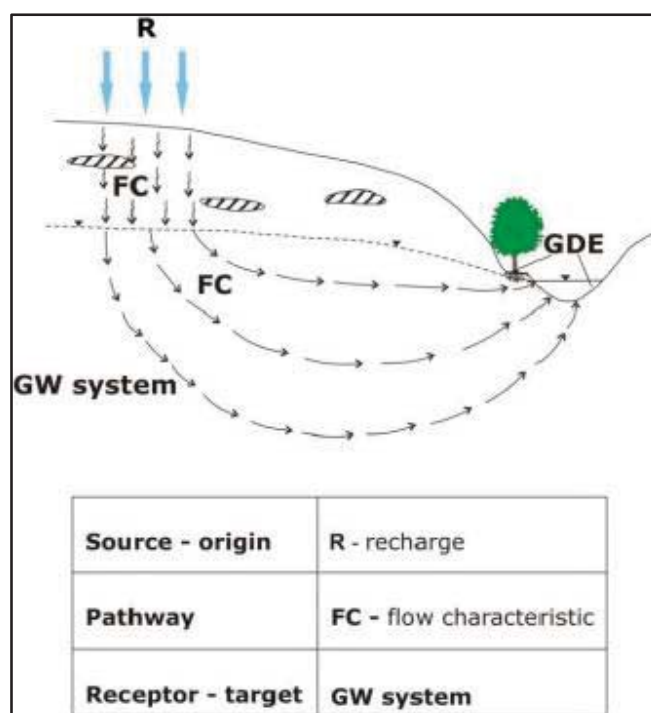
Source: www.thegenesisproject.eu.

Figure 10. Basic concepts defining the intrinsic vulnerability in relation to work packages (WP) of the GENESIS project.

The basic principles of the intrinsic vulnerability of the COST Action 620 were assessed on the assumption of groundwater vulnerability based on the properties controlling the transport of a conservative contaminant which behaves like water molecules (Daly et al., 2002; Goldscheider, 2002). These include factors such as dilution, dispersion, and advective transit time, which indicate when a substantial amount of contaminant can get to the water table. Transport of any contaminant always depends on interaction between the specific properties of the contaminant and specific properties of the area and the media the contaminant passes through. For instance, pesticide mass transport depends on type and content of organic matter and mobility of bacteria, particularly in a soakaway, depends on media pore sizes and

pathogen residence time. Mass transport of heavy metals depends on the cation exchange capacity of the media and nitrate movement influenced by media redox potentials.

This means that the actual parameters needed in determining arrival time on the field for intrinsic vulnerability are permeability and lithological thickness for intrinsic vulnerability and an addition of relevant factors of contaminants (e.g., redox potential, type, and content of clay minerals and organic matter) for specific vulnerability mapping (Goldscheider, 2002). Therefore, a very simplified site-specific intrinsic vulnerability method for future vulnerability assessment should be based on the permeability of overlying lithology above the water table and the overall depth from the surface to the water table. This simple vulnerability methodology is similar to the work packages (WP) of the GENESIS Project (2013) shown in Figure 10.

REFERENCES

Akhavan, S., Mousavi, S. F., Abedi-Koupai, J., Abbaspour, K. C. 2011. Conditioning DRASTIC model to simulate nitrate pollution case study: Hamadan–Bahar plain. *Environ Earth Sci* 63: pp. 1155–1167.

Al-Adamat, R. A. N., Foster, I. D. L., Baban, S. M. J. 2003. Groundwater vulnerability and risk mapping for the basaltic aquifer of the Azraq Basin of Jordan using GIS, remote sensing and DRASTIC. *Appl Geogr* 23: pp. 3–324.

Albinet, M, Margat, J. 1970. Cartographie de la vulnérabilité à la pollution des nappes deau souterraine Orleans, France. *Bull BRGM 2ème série* 4: pp. 13–22.

Al-Hanbali, A., Kondoh, A. 2008. Groundwater vulnerability assessment and evaluation of human activity impact (HAI) within the Dead Sea groundwater basin, Jordan. *Hydrogeology Journal* 16: pp. 499–510.

Aller, L., Bennett, T., Lehr, J., et al., 1987. DRASTIC: A standardised system for evaluating ground water pollution potential using hydrogeologic settings. National Water Well Association, Dublin, OH and Environmental Protection Agency, Ada, OK. EPA-600/2-87-035.

Andersen, L.J., Gosk, E. 1987. Applicability of vulnerability maps. In: Duijvenbooden, W. van, Waegeningh, H. G. van (eds.) *Vulnerability of Soil and Groundwater to Pollutants: Proceedings and Information* 38: pp. 321–332. TNO Committee on Hydrological Research, The Hague, The Netherlands.

Andreo, B., Goldscheider, N., Vadillo, I., et al., 2006. Karst groundwater protection: First application of a Pan-European Approach to vulnerability, hazard and risk mapping in the Sierra de Libar (southern Spain). *Science of the Total Environment* 357(1-3): pp. 54–73.

Andreo, B., Ravbar, N., Vıas, J. M. 2009. Source vulnerability mapping in carbonate (karst) aquifers by extension of the COP method: Application to pilot sites. *Hydrogeology Journal* 17(3): pp. 749–758.

Babiker, I. S., Mohammed, M. A. A., Hiyama, T., Kato, K. 2005. A GIS-based DRASTIC model for assessing aquifer vulnerability in Kakamigahara Heights, Gifu Prefecture, central Japan. *Science of the Total Environment* 345: pp. 127–140.

Bachmat, Y., Collin, M. 1987. Mapping to assess groundwater vulnerability to pollution. In: Duijvenbooden, W. van, Waegeningh, H.G. van (eds). *Vulnerability of Soil and Groundwater to Pollutants: Proceedings and Information* 38: pp. 297–307. TNO Committee on Hydrological Research, The Hague, The Netherlands.

Barber, C., Bates, L. E., Barron, R., Allison, H. 1993. Assessment of the relative vulnerability of groundwater to pollution: A review and background paper for the conference workshop on vulnerability assessment. *J Austr Geol Geophys* 14(2/3): pp. 1147–1154.

Basu, N. B., Jindal, P., Schilling, K. E., et al., 2012. Evaluation of analytical and numerical approaches for the estimation of groundwater travel time distribution. *Journal of Hydrology* 475: pp. 65–73.

Bear, J. 1979. *Hydraulics of Groundwater*. McGraw-Hill, New York. p. 567.

BRGM (The French Geological Survey). 1979. *Maps of Ground Water Vulnerability to Contamination, 31 sheets, 1:50,000* [in French]. BRGM, Orlèans, France.

Brosig, K., Geyer, T., Subah, A., Sauter, M. 2008. Travel time based approach for the assessment of vulnerability of karst groundwater: The transit time method, *Environ Geol 54:* pp. 905–911.

Brouyère, S., Jeannin, P. J., Dassargues, A., et al., 2001. Evaluation and validation of vulnerability concepts using a physical based approach. Seventh Conference on Limestone Hydrology and Fissured Media, Besançon. *Sci Tech Envir Mèm* 13: pp. 67–72.

Carter, A. D., Palmer, R. C., Monkhouse, R. A. 1987. Mapping the vulnerability of groundwater to pollution from agricultural practice, particularly with respect to nitrate. In: Duijvenbooden, W. van, Waegeningh, H. G. van (eds). *Vulnerability of Soil and Groundwater to*

Pollutants. TNO Committee on Hydrological Research, The Hague, The Netherlands. *Proceedings and Information* 38: pp. 333–342.

Chen, W., Kao, J. 1997. Fuzzy DRASTIC for landfill siting. In: *Proceedings of the 13th International Conference on Solid Waste Technology and Management, vol. 1*. Widener University.

Civita, M. 1994. *Le Carte della Vulnerabilita Degli Acquiferiall Inquinamento: Teoria e Practica (Aquifer Vulnerability Maps to Pollution)*. Bologna, Pitagora, Italy.

Civita, M., De Regibus, C. 1995. Sperimentazione di alcune metodologie per la valutazione della vulnerabilita degli aquiferi, *Q Geol Appl* 3: pp. 63–71.

Civita, M., De Maio, M. 2000. SINTACS R5, a new parametric system for the assessment and automatic mapping of groundwater vulnerability to contamination. Publ. 2200 del GNDCI-CNR. Pitagora Editrice, Bologna, Italy. p. 240.

Connell, L. D., Daele, G. V. D. 2003. A quantitative approach to aquifer vulnerability mapping. *J Hydrol* 276(1–4): pp. 71–88.

Daly, D., Drew, D. 1999. Irish methodologies for karst aquifer protection. In: Beck, B. (ed). *Hydrogeology and Engineering Geology of Sinkholes and Karst*. Balkema, Rotterdam, The Netherlands. pp. 267–272.

Daly, D., Drew, D., Goldscheider, N., Hotzl, H. 2000. Suggested Outline of a European Approach to Mapping Groundwater Vulnerability. Recommendations to Working Group 1 of COST 620, Results of the Task Group Meeting, European Approach. Karlsruhe (unpublished). p. 6.

Daly, D., Dassargues, A., Drew, D., et al., 2002. Main concepts of the "European Approach" for (karst) groundwater vulnerability assessment and mapping. *Hydrogeology Journal* 10(2): pp. 340–345.

Dixon, B. 2001. Application on neuro-fuzzy techniques to predict groundwater vulnerability in Northwest Arkansas. PhD thesis, University of Arkansas. Fayetteville, AK,.

Dixon, B. 2004. Prediction of groundwater vulnerability using integrated GIS-based neuro-fuzzy techniques. *Journal of Spatial Hydrology* 4(2).

Dixon, B. 2005. Applicability of neuro–fuzzy techniques in predicting groundwater vulnerability: A GIS–based sensitivity analyses. *J Hydrol* 309, pp. 17–38.

Dixon, B. 2005a. Groundwater vulnerability mapping: A GIS and fuzzy rule based integrated tool. *Applied Geography* 25(4): pp. 327–347.

Dixon, B., Scott, H. D., Dixon, J. C., Steele, K. F. 2002. Prediction of aquifer vulnerability to pesticides using fuzzy rule-based models at the regional scale. *Phys Geogr* 23: pp. 130–153.

Doerfliger, N. 1994. Réflexion sur la variabilité des fonctions de transfert obtenues par traçage en milieu karstique (jura tabulaire et alpes du domaine helvétique). *Bulletin Hydrogéologie* 13: pp. 69–86.

Doerfliger, N., Jeannin, P. Y., Zwahlen, F. 1999. Water vulnerability assessment in karst environments: A new method of defining protection areas using a multi-attribute approach and GIS tools (EPIK method). *Environmental Geology* 39(2): pp. 165–176.

Doerfliger, N., Plagnes, V., Kavouri, K. 2010. PaPRIKa, a multi-criteria vulnerability method as a tool for sustainable management of karst aquifers: Example of application on a test site in SW France. *Sustainability of the Karst Environment*. p. 49.

Eberts, S. M., Böhlke, J. K., Kauffman, L. J., Jurgens, B. C. 2012. Comparison of particle tracking and lumped-parameter age-distribution models for evaluating vulnerability of production wells to contamination. *Hydrogeology Journal* 20*:* pp. 263–282.

European Commission. COST Action 620. 2003. *Vulnerability and risk mapping for the protection of carbonate (karst) aquifers: Scopes-goals-results*. Zwahlen, F. (ed). European Commission, Directorate-General, Science, Research and Development, Luxembourg. pp. 1–42.

Fenton, O., Schulte, R. P. O., Jordan, P., et al., 2011. Time-lag: A methodology for the estimation of vertical and horizontal travel and flushing timescales to nitrate threshold concentrations in Irish aquifers. *Environmental Science and Policy* 14(4): pp. 419–431.

Focazio, M. J., Reilly, T. E., Rupert, M. G., Helsel, D. R. 2001. Assessing groundwater vulnerability to contamination: Providing scientifically defensible information for decision makers *U. S. Geological Survey Circular* 1224.

Foster, S. S. D. 1987. Fundamental concepts in aquifer vulnerability, pollution risk and protection strategy. In: van Duijvenboden, W., van Waegeningh, H. G. (ed). *Vulnerability of Soil and Groundwater to Pollutants*. TNO Comm. on Hydro. Research, The Hague, The Netherlands*. Proceeding and Information* 38: pp. 69–86.

Fried, J. J. 1987. Groundwater resources in the European Community: Second phase, vulnerability-quality (synthetical report, unpublished).

Frind, E. O., Molson, J. W., Rudolph, D. L. 2006. Well vulnerability: A quantitative approach for source water protection. *Ground Water* 4(5): pp. 732–742.

Fritch, T. G., McKnight, C. L., Yelderman, J. C., Arnold, J. G. 2000. Aquifer vulnerability assessment of the paluxy aquifer, Central Texas, USA, using

GIS and a modified DRASTIC approach. *Environ Manage* 25: pp. 337–345.

Gemitzi, A., Petalas, C., Tsihrintzi, V. A., Pisinaras, V. 2006. Assessment of groundwater vulnerability to pollution: A combination of GIS, fuzzy logic and decision making techniques. *Environ Geol* 49: pp. 653–673.

GENESIS Project. 2013. *Critical Review of Methods for Assessment of Vulnerability of Groundwater Systems: Groundwater and Dependent Ecosystems: New Scientific and Technological Basis for Assessing Climate Change and Land-use Impacts on Groundwater.* pp. 1–115. www.thegenesisproject.eu.

Gogu, R. C., Dassargues, A. 2000a. Current trends and future challenges in groundwater vulnerability assessment using overlay and index methods. *Environ Geol* 39(6): pp. 549–559.

Gogu, R. C., Dassargues, A. 2000b, Sensitivity analysis for the EPIK method of vulnerability assessment in a small karstic aquifer, southern Belgium. *Hydrogeol J* 8(3): pp. 337–345.

Gogu, R. C., Hallet, V., Dassargues, A. 2003. Comparison of aquifer vulnerability assessment techniques: Application to the Néblon river basin, Belgium. *Environ Geol* 44: pp. 881–892.

Goldscheider, N. 2002. Hydrogeology and vulnerability of karst systems: Examples from the Northern Alps and Swabian Alb. PhD thesis. University of Karlsruhe. pp. 1–259.

Goldscheider, N. 2005. Karst groundwater vulnerability mapping: Application of a new method in the Swabian Alb, Germany. *Hydrogeology Journal* 13(4): pp. 555–564.

Goldscheider, N., Hötzl, H., Fries, W., Jordan, P. 2001. Validation of a vulnerability map (EPIK) with tracer tests. In: Mudry, J., Zwahlen, F. (eds). Seventh Conference on Limestone Hydrology and Fissured Media, Besançon, France. University de Franche-Comté, Besançon. pp. 167–170.

Goldscheider, N., Klute, M., Sturm, S., Hötzl, H. 2000. The PI method: A GIS-based approach to mapping groundwater vulnerability with special consideration of karst aquifers. *Z Angew Geol* 46(3): pp. 157–166.

Goossens, M., Van Damme, M. 1987. Vulnerability mapping in Flanders, Belgium. Vulnerability of soil and groundwater to pollutant. In: Duijvenbooden, W. van, Waegeningh, G. H. (eds). TNO Committee on Hydrological Research, The Hague, The Netherlands. *Proceedings and Information* 38: pp. 355–360.

Gvirtzman, H., Ronen, D., Magaritz, M. 1986. Anion exclusion during transport through the unsaturated zone. *Journal Hydrol* 87(314): pp. 267–284.

Haith, D. A., Laden, E. M. 1986. Screening of groundwater contamination by travel time distributions. *Journal of Environmental Engineering* 115(3): pp. 497–512.

Herbst, M., Hardelauf, H., Harms, R., et al., 2005. Pesticide fate at regional scale: Development of an integrated model approach and application. *Physics and Chemistry of the Earth* 30(8–10): pp. 542–549.

Herlinger, R., Jr., Viero, A. P. 2006. Evaluation of contaminants retention in soils from Viamao District, Rio Grande do Sul State, Brazil. *Environ Geol* 50: pp. 47–54.

Herrmann, F., Berthold, G., Fritsche, J. G., et al., 2012. Development of a conceptual hydrogeological model for the evaluation of residence times of water in soil and groundwater: The state of Hesse case study, Germany. *Environ Earth Sci* 67: pp. 2239–2250.

Hojberg, A.L., Kjær, J., Nolan, B. T. 2006. Characteristics of European groundwater vulnerability scenarios. Report DL10 of the FP6 EU-funded FOOTPRINT project. p. 38.. www.eufootprint.org.

Holting, B. 1996. *Hydrogeologie*. Enke, Stuttgart, Germany.

Holting, B., Haertle, T., Hohberger, K. H., et al., 1995. Konzept zur Ermittlung der Schutzfunktion der Grundwasserüberdeckung [Concept to assess the protective function of the layers above the groundwater surface]. *Geol Jahrb Hannover C* 63: pp. 5–24.

Jeannin, P. Y., Cornaton, F., Zwahlen, F., Perrochet, P. 2001. VULK: A tool for intrinsic vulnerability assessment and validation. In: Mudry, J., Zwahlen, F. (eds). Seventh Conference on Limestone Hydrology and Fissured Media. Besançon, France, University de Franche-Comté, Besançon. pp. 185–190.

Kleczkowski, A. S. 1990. *The Map of the Critical Protection Areas (CPA) of the Major Groundwater Basins (MGWB) in Poland, 1:500,000*. Central Research Program, Environmental Management and Protection, AGH, University of Science and Technology, Krakow, Poland. p. 44.

Krogulec, E. 2004. Groundwater vulnerability to contamination in the central part of Vistula River Valley, Kampinoski National Park, Poland. In: Witkowski, A. J., Kowalczyk, A., Vrba, J. (eds). *Selected Papers from the Groundwater Vulnerability Assessment and Mapping, Ustron, Poland.* pp. 124–132.

Kunkel, R., Wendland, F. 1997. WEKU: A GIS-supported stochastic model of groundwater residence times in upper aquifers for the supra-regional groundwater management. *Environ Geol* 30(1–2): pp. 1–9.

Kunoth, K. 2000. GIS-gestützte Vulnerabilitätskartierung als Beitrag zur Entwicklung der Europäischen Methode unter besonderer Berücksichtigung der Schutzfunktion der Grundwasserüberdeckung am Beispiel des alpinen Karstgebietes Gottesacker-Hochifen (Vorarlberg, Bayern). master's thesis, University Karlsruhe, Karlsruhe, Germany (unpublished), p. 94.

Lasserre, F., Razack, M., Banton, O. 1999. A GIS-linked model for the assessment of nitrate contamination in groundwater. *J Hydrol* 224(3–4): pp. 81–90.

Leyland, R. C. 2008. Vulnerability mapping in Karst terrains, exemplified in the wider Cradle of Human World Heritage Site. Dept. of Geology, University of Pretoria, Pretoria, South Africa. pp. 1–114.

Liggett, J. E., Talwar, S. 2009. Groundwater vulnerability assessments and integrated water resource management. *Streamline Watershed Management Bulletin* 13(1): p. 19.

Lobo-Ferreira, J. P., Oliveira, M. M. 1997. DRASTIC groundwater vulnerability mapping of Portugal: Groundwater: An endangered resource. In: Proceedings of the 27th Congress of the International Association for Hydraulic Research. San Francisco, CA. pp. 132–137.

Lodwick, W. A., Monson, W., Svoboda, L. 1990. Attribute error and sensitivity analysis of map operations in geographical information systems: Suitability analysis. *Ins J Geogr Inform Syst* 4(4): pp. 413–428.

Lowe, M., Wallace, J., Burk, N., et al., 2005. Groundwater sensitivity and vulnerability to pesticides, Salt Lake Valley. Miscellaneous Publication 05-7, Utah Geological Survey. pp. 1–25.

Macioszczyk, T. 1992. Parametry hydrogeologiczne. In: *W sluzbie polskiej hydrogeologii, Wyd.* AGH, Krakow, Poland. pp. 191–196.

Magiera, P. 2000. Methoden zur Abschätzung der Verschmutzungsempfindlichkeit des Grundwassers. *Grundwasser* 3(2000): pp. 103–114.

Margat, J. 1968. Vulnerabilite des nappes deau souterraine a la pollution: Bases de la cartographie. Bureau de Recherches Geologiques et Minieres, Orleans, France. 68 SGL 198 HYD.

Marin, A. I., Andreo, B., Jimenez-Sanchez, M., et al., 2012. Delineating protection areas for caves using contamination vulnerability mapping

techniques: The case of Herrerıas Cave, Asturias, Spain. *Journal of Cave and Karst Studies* 74(1): pp. 103–115.

McLay, C. D. A., Dragden, R., Sparling, G., Selvarajah, N. 2001. Predicting groundwater nitrate concentrations in a region of mixed agricultural land use: A comparison of three approaches. *Environmental Pollution* 115: pp. 191–204.

Meinardi, C. R., Beusen, A. H. W., Bollen, M. J. S., et al., 1982. Vulnerability to diffuse pollution and average nitrate contamination of European soils and groundwater. *Water Science and Technology* 31(8): pp. 159–165.

Mende, A., Astorga, A., Neumann, D. 2007. Strategy for groundwater management in developing countries: A case study in northern Costa Rica. *J Hydrol* 334(1–2): pp. 109–24.

Merchant, J. W. 1994. GIS-based groundwater pollution hazard assessment: A critical review of the DRASTIC model. *Photogramm Eng Remote Sensing* 60(9): pp. 1117–1127.

Moore, John, S. 1990. SEEPAGE: A system for early evaluation of the pollution potential of agricultural groundwater environments. Geology Technical Note 5. USDA, SCS, Northeast Technical Center,.

Murat, V., Rivera, A., Pouliot, J., Miranda-Salas, M., Savard, M.M. 2004. Aquifer vulnerability mapping and GIS: A proposal to monitor uncertainty associated with spatial data processing. *Geofi Int* 43(4): pp. 551–565.

Napolitano, P. Fabbri, A. G. 1996. Single-parameter sensitivity analysis for aquifer vulnerability assessment using DRASTIC and SINTACS. In: K. Kovar, K., Nachtnebel, H. P. (eds). *Application of Geographic Information Systems in Hydrology and Water Resources Management.* Wallingford, IAHS Press, pp. 559–566.

National Research Council (NRC). 1993. Groundwater vulnerability assessment: Contamination potential under conditions of uncertainty. National Academy Press, Washington, DC. Natural Resources Canada, 2005.

Neukum, C., Azzam, R. 2009. Quantitative assessment of intrinsic groundwater vulnerability to contamination using numerical simulations. *Science of the Total Environment* 408(2): pp. 245–254.

Neukum, C., Hötzl, H., Himmelsbach, T. 2008. Validation of vulnerability mapping methods by field investigations and numerical modeling. *Hydrogeology Journal* 16(4): pp. 641–658.

Nguyet, V. T. M., Goldscheider, N. 2006. Tracer tests, hydrochemical and microbiological investigations as a basis for groundwater protection in a

remote tropical mountainous karst area, Vietnam. *Hydrogeology Journal* 14: pp. 1147–1159.

Nguyet, V. T. M., Goldscheider, N. 2007. A simplified methodology for mapping groundwater vulnerability and contamination risk, and its first application in a tropical karst area, Vietnam. *Hydrogeology Journal* 14: pp. 1666–1675.

Oke, S. A. 2015. Evaluation of the vulnerability of selected aquifer systems in the Eastern Dahomey Basin, SW Nigeria. PhD dissertation, University of Free State Bloemfontein, South Africa. pp. 12–147.

Oke, S. A., Vermulen, D. 2016a: Comparison of four vulnerability approaches to mapping of shallow aquifers of Eastern Dahomey Basin of Nigeria. Geophysical Research Abstracts 18, EGU2016-882.

Oke, S. A., Vermeulen, D., Gomo, M. 2016b. Aquifer vulnerability assessment of the Dahomey Basin using the RTt method. *Environmental Earth Sciences* 75(11): pp. 1–9.

Panagopoulos, G. P., Antonakos, A. K., Lambrakis, N. J. 2006. Optimization of the DRASTIC method for groundwater vulnerability assessment via the use of simple statistical methods and GIS. *Hydrogeology Journal* 14: pp. 894–911.

Perrin, J., Pochon, A., Jeannin P. Y., Zwahlen, F. 2004. Vulnerability assessment in karstic areas: Validation by field experiment. *Environmental Geology 46*(2): pp. 237–245.

Piscopo, G. 2001. *Groundwater Vulnerability Map Explanatory Notes: Castlereagh Catchment.* Australia NSW Department of Land and Water Conservation, Parramatta.

Province of Ontario. 2006. *Assessment Report: Draft Guidance Module 3: Groundwater Vulnerability Analysis*. Ministry of the Environment, Toronto, Canada: Queens Printer.

Rahman, A. 2008. A GIS based DRASTIC model for assessing groundwater vulnerability in shallow aquifer in Aligarh, India. *Appl Geogr* 28(1): pp. 32–53.

Ramos-Leal, J. A., Rodrıguez-Castillo, R. 2003. Aquifer vulnerability mapping in the Turbio River Valley, Mexico: A validation study. *Geofi Int* 42: pp. 141–145.

Rao, S. N. 2008. Factors controlling the salinity in groundwater in parts of Guntur district, Andhra Pradesh, India. *Environ Monit Assess* 138: pp. 327–341.

Rao, P., Hornsby, A., Jessup, R. 1985. Indices for ranking the potential for pesticide contamination of groundwater. In: *Proceedings of Soil Crop Science Soc, Florida* 44: pp. 1–8.

Ravbar, N. 2007. Vulnerability and risk mapping for the protection of karst waters in Slovenia: Application to the catchment of the Podstenjšek springs. PhD thesis, University of Nova Gorica, Slovenia.

Ravbar, N., Goldscheider, N. 2007. Proposed methodology of vulnerability and contamination risk mapping for the protection of karst aquifers in Sloveni. *Acta Carsol* 36(3): pp. 397–411.

Ravbar, N., Goldscheider, N. 2009. Comparative application of four methods of groundwater vulnerability mapping in Slovene karst catchment. *Hydrogeology Journal* 17(3): pp. 725–733.

Robins, N. S. 1998. Recharge the key to groundwater pollution and aquifer vulnerability. In: *Groundwater Pollution, Aquifer Recharge and Vulnerability*. Robins, N. S. (ed). Geological Society, London Special Publications.

Ross, M., Richard, M., Lefebvre, R., et al., 2004. Assessing rock aquifer vulnerability using downward advective time from a 3D model of surficial geology: Case studies from the St. Lawrence Lowlands, Canada. *Geofisica International* 43(4): pp. 591–602.

Saayman, I. C., Beekman, H. E., Adams, S., et al., 2007. *Assessment of Aquifer Vulnerability in South Africa. WRC Report* 1432(1): pp. 1–111.

Saidi, S., Bouri, S., Ben Dhia, H., Anselme, B. 2011a. Assessment of groundwater risk using intrinsic vulnerability and hazard mapping: Application to Souassi aquifer. *Tunisian Sahel, Agric Water Manag* 98(10): pp. 1671–1682.

Saidi, S., Bouri, S., Ben Dhia, H. 2011b. Sensitivity analysis in groundwater vulnerability in the Mahdia-Ksour Essaf aquifer. *Hydrological Science Journal* 56(2): pp. 288–304.

Shahid, S. 2000. A study of groundwater pollution vulnerability using DRASTIC/GIS, west Bengal, India. *Journal of Environmental Hydrology* 8: p. 124.

Shirazi, S. M., Imran, H. M., Akib, S., et al., 2013. Groundwater vulnerability assessment in the Melaka State of Malaysia using DRASTIC and GIS techniques, *Environ Earth Sci.* Springer-Verlag, Berlin, Germany.

Sinreich, M., Cornaton, F., Zwahlen, F. 2007. Evaluation of reactive transport parameters to assess specific vulnerability in karst systems, In: Witkowski, A.J., Kowalczyk, A., Vrba, J. *Groundwater Vulnerability*

Assessment and Mapping: Selected Papers on Hydrogeology 11: pp. 21–32.

Sorichetta, A. 2010. *Groundwater vulnerability assessment using statistical methods*. PhD thesis, Scuola di Dottorato in Terra, Ambiente e Biodiversita. Universita degli Studidi Milano, Italy.

Sousa, M. R., Jones, J. P., Frind, E. O., Rudolph, D. L. 2013. A simple method to assess unsaturated zone time-lag in the travel time from ground surface to receptor. *Journal of Contaminant Hydrology* 144(1): pp. 138–151.

Stigter, T. Y., Ribeiro, L., Dill, A. M. M. C. 2006. Evaluation of an intrinsic and a specific vulnerability assessment method in comparison with groundwater salinisation and nitrate contamination levels in two agricultural regions in the south of Portugal. *Hydrogeol J* 14: pp. 79–99.

Teso, R., Poe, M., Younglove, T., McCool, P. 1996. Use of logistic regression and GIS modelling to predict groundwater vulnerability to pesticides. *J Environ Qual* 25: pp. 425–432.

Thirumalaivasan, D., Karmegam, M., Venugopal, K. 2003. AHPDRASTIC: Software for specific aquifer vulnerability assessment using DRASTIC model and GIS. *Environ Model Software* 18: pp. 645–656.

Van Stempvoort, D., Ewert, L., Wassenaar, L. 1993. Aquifer vulnerability index: A GIS compatible method for groundwater vulnerability mapping. *Canadian Water Resources Journal* 18: pp. 25–37.

Vias, J. M., Andreo, B., Perles, M. J., Carrasco, F. 2005. A comparative study of four schemes for groundwater vulnerability mapping in a diffuse flow carbonate aquifer under Mediterranean climatic conditions. *Environ Geol* 47(4): pp. 586–595.

Vías, J. M., Andreo, B., Perles, J. M., Carrasco, F., Vadillo, I. 2006. Proposed method for groundwater vulnerability mapping in carbonate (karstic) aquifers: The COP method application in two pilot sites in southern Spain. *Hydrogeology Journal* 14(6): pp. 912–925.

Vierhuff, H., Wagner, W., Aust, H. 1981. Die Grundwasservorkommen in der Bundesrepublik Deutschland. *Geol Jb* C30: pp. 3–110.

Villumsen, A., Jacobsen, O. S., Sonderskov, C. 1982. Mapping the vulnerability of groundwater reservoirs with regard to surface pollution. In: *Geological Survey of Denmark: Yearbook 1982*. Copenhagen, Denmark. pp. 17–38.

Voigt, H. J., Heinkele, T., Jahnke, C., Wolter, R. 2004. Characterisation of groundwater vulnerability to fulfil requirements of the water framework directive of the European Union. *Geofísica Internacional* 43: pp. 567–574.

Von Hoyer, M., Sofner, B. 1998. Groundwater vulnerability mapping in carbonate (karst) areas of Germany. Federal Institute for Geosciences and Natural Resources. 117854. Hanover, Germany.

Vrba, J., Zaporozec, A. 1994. Guidebook on mapping groundwater vulnerability. IAH, HeiseVerlag, Hanover, Germany. International Contributions to Hydrogeology 16.

WFD (Water Framework Directive). 2000. Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for community action in the field of water policy. *Official Journal of the European Communities* 327(1).

Witczak, S., Duda, R., Zurek, A. 2007. The Polish concept of groundwater vulnerability mapping. In: Witkowski, A.J., Kowalczyk, A., Vrba J. (eds). *Groundwater Vulnerability Assessment and Mapping: Selected Papers on Hydrogeology* 11. pp. 45–59.

Witczak, S., Szczepański, A., Mikołajków, J., Skrzypczyk, L. 2010. Protection of groundwater quality and quantity of strategic groundwater resources of the major groundwater basins. *Przegląd Geol* 58(9/1): pp. 754–761.

Witczak, S., Zurek, A. 2002. Wykorzystanie map glebowo-rolniczych w ocenie ochronnej roli gleb dla wod podziemnych, In: Kleczkowski, A. S. (ed). *Metodyczne podstawy ochrony wod podziemnych*. Projekt badawczy KBN. Wyd. AGH, Krakow, Poland.

Witczak, S., Zurek, A. 2002. Vulnerability assessment in fissured aquifers. In: *Groundwater Quality and Vulnerability*. Silesian University, Sosnowiec. pp. 241–254.

Witkowski, A. J., Kowalczyk, A. 2004. A simplified method of regional groundwater vulnerability assessment. In: Proceedings of Groundwater Vulnerability Assessment and Mapping. Ustron, Poland.

Wosten, J. H., Bannink, J. J., De Gruijter, J., Bouma, J. 1986. A procedure of identifying different groups of hydraulic conductivity and moisture retention curves for soils horizons. *Journal of Hydrology* 86: pp. 133–145.

Yu, Ch., Yao, Y., Hayes, G., Zhang, B., Zheng, Ch. 2010. Quantitative assessment of groundwater vulnerability using index system and transport simulation, Huangshuihe catchment, China. *Science of the Total Environment* 408: pp. 6108–6116.

Zwahlen, F. 2004. Vulnerability and risk mapping for the protection of carbonate (karst) aquifers: Final report. European Cooperation in Science and Technology (COST), Action 620. EU Publications Office, Brussels, Belgium. pp. 1–42.