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

T. Y. Stigter · L. Ribeiro · A. M. M. Carvalho Dill

Abstract The applicability of two vulnerability assessment methods in evaluating the impact of agricultural activities on groundwater quality, is tested in two areas in the south of Portugal with modest results. Intensive citri- and horticulture require large amounts of fertiliser and water supplied by irrigation, which induces groundwater salinisation and contamination by nitrates. The degree of contamination varies highly within and between the study areas and is related to hydrogeological factors as well as intensity of agricultural practices. Vulnerability mapping is performed with the intrinsic DRASTIC method and the specific Susceptibility Index (SI), which is an adaptation of DRASTIC. These methods can constitute useful groundwater management tools, for instance when designating new Nitrate Vulnerable Zones as defined in the European Directive 91/676/EEC. However, in the case of DRASTIC, little correspondence exists between the most vulnerable and the most contaminated areas. This is mainly a result of underestimating the dilution capacity and overemphasising the attenuating potential of the unsaturated zone and aquifer, as both chloride and nitrate prove to be very stable contaminants. By including a parameter for land use, SI manages to produce more reliable results, although in many areas the vulnerability is overestimated.

Résumé L'application de deux méthodes de calcul de la vulnérabilité permettant d'évaluer l'impact des activités agricoles sur la qualité des eaux souterraines, est testée dans deux zones du Sud du Portugal, avec des résultats modestes. La citriculture et l'horticulture intensives nécessitent de grandes quantités e fertilisants et d'eau souterraine pour l'irrigation, ce qui induit la salinisation et la contamination des eaux souterraines par les nitrates. Le degré de contamination varie grandement à l'intérieur et entre les zones d'études, en fonction des facteurs hydrogéologiques et de l'intensité des pratiques agricoles. La cartographie de la vulnérabilité est mise en oeuvre via la méthodologie DRASTIC et l'Index de Susceptibilité (SI) spécifique, qui est une adaptation de la méthode DRASTIC. Ces méthodes êuvent constituer des outils de management des eaux souterraines, par exemple lors de la désignation de nouvelles zones de vulnérabilité aux Nitrates selon la n Directive Européenne 91/676/EEC. Par ailleurs dans le cas de DRASTIC, de petites correspondances existent entre les zones les plus vulnérables et les plus contaminées. Ceci est principalement le résultat d'une sous-estimation de la capacité de dilution et de la sur-accentuation du potentiel d'atténuation de la zone non-saturée de l'aquifère, car et le chlore et les nitrates sont des contaminants très stables. En incluant un paramètre d'utilisation des sols, SI produit des résultats plus réalistes, bien que dans de nombreuses zones la vulnérabilité soit surestimée.

Resumen Se evalúa la aplicabilidad de dos métodos de estimación de vulnerabilidad en evaluar el impacto de actividades agrícolas en la calidad del agua subterránea para dos áreas en el sur de Portugal obteniendo resultados modestos. La horticultura y citricultura intensiva requiere grandes cantidades de fertilizantes y agua abastecida por riego, lo cual induce salinización de agua subterránea y contaminación por nitratos. El grado de contaminación varía fuertemente dentro y entre las áreas de estudio y se relaciona con factores hidrogeológicos así como con la intensidad de las prácticas agrícolas. El mapeo de vulnerabilidad se lleva a cabo con el método intrínsico DRASTIC y el Índice de Susceptibilidad específica (SI), el cual es una adaptación de DRASTIC. Estos métodos pueden constituir herramientas de manejo de aguas subterráneas útiles, por ejemplo al designar nuevas Zonas Vulnerables por Nitratos del modo que se definen en la Directiva Europea 91/676/EEC. Sin embargo, en el caso de DRASTIC, existen poca correspondencia entre las zonas más vulnerables y las áreas más contaminadas. Esto

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se debe principalmente a la subestimación de la capacidad de dilución y a al sobre énfasis del potencial de atenuación de la zona no saturada y el acuífero, ya que tanto cloruro como nitrato han probado ser contaminantes muy estables. Al incluir un parámetro del uso de la tierra, SI genera resultados más confiables, aunque en muchas áreas se sobrestima la vulnerabilidad.

Keywords Vulnerability · Contamination · Agriculture · Dilution · Portugal

Introduction

The definition of the term vulnerability is not unambiguous. First of all, vulnerability is often defined merely with regard to water quality, though it may include aspects of water quantity. According to Vrba and Zoporozec (1994), one of the earliest definitions found in the literature is that of Albinet and Margat (1970) who stated that aquifer vulnerability is “the possibility of percolation and diffusion of contaminants from the ground surface into natural water-table reservoirs under natural conditions”. Many other attempts to define groundwater vulnerability have been made since then, some of which were presented at the first major conference within this topic, ‘International Conference on Vulnerability of Soil and Groundwater to Pollutants’, held in 1987 in the Netherlands (Van Duijvenbooden and Van Waegeningh 1987). Vrba and Zoporozec (1994) give a good overview of these definitions in their ‘Guidebook on Mapping Groundwater Vulnerability’, including those provided by Bachmat and Collin (1987), Foster (1987) and the Committee on Techniques for Assessing Ground Water Vulnerability (1993), among others. The same authors propose a final definition of vulnerability as “an intrinsic property of a groundwater system that depends on the sensitivity of that system to human and/or natural impacts”. They distinguish intrinsic (or natural) vulnerability from specific (or integrated) vulnerability; the first term defined solely as a function of hydrogeological factors and the latter term defined by the potential impacts of specific land uses and contaminants. In other words, specific vulnerability integrates the contamination risk placed upon aquifers by human activities.

Vulnerability is not an absolute characteristic, but rather a relative, non-measurable, dimensionless property indicating where contamination is most likely to occur. The first attempts to represent it in maps were made by Margat (1968) in France. Since then, many methods and techniques concerning its graphical and numerical representation, which can be used for managerial or decision-making purposes, have been developed. These methods can be grouped into three basic groups, namely: hydrogeological setting methods, parametric methods and numerical models (Vrba and Zoporozec 1994). According to Canter (1997) and the Committee on Techniques for Assessing Ground Water Vulnerability (1993), statistical methods should also be considered. Hydrogeological setting methods, generally suitable for large areas and directly related to the existing hydrogeological units, are the most qualitative assessment methods. Numerical models can be powerful tools, but only produce reliable results when large amounts of specific data are available.

There has been a lot of discussion on whether or not vulnerability maps provide reliable estimates of the contamination potential of groundwater bodies. While in many cases good and useful applications exist (Vrba and Zoporozec 1994), in others large discrepancies are found between the vulnerability maps and groundwater contamination levels (e.g. Garrett et al. 1989; Rosen 1994; Rupert 2001; Stigter et al. 2002a). Vulnerability assessment is not always an easy task and oversimplification or inadequate description of the hydrogeological system can endanger the reliability of the resulting maps. Difficulties in obtaining reliable field data can also constitute a serious limitation on the quality of vulnerability maps. Furthermore, many groundwater vulnerability assessment methods only include intrinsic parameters; assuming therefore that their application is valid for all potential contaminants and independent of land use. The advantages of mapping vulnerability for a specific pollutant or group of pollutants were pointed out by Andersen and Gosk (1987) and Foster (1987), among others.

The only way of gaining confidence in vulnerability mapping is by comparing the results of various techniques and analysing their consistency in practical case studies where contamination has already occurred. Gogu and Dassargues (2000) point out that such studies constitute one of the important research challenges. The main objective of this article is to evaluate the applicability of two vulnerability assessment methods to the problem of diffuse nitrate contamination and groundwater salinisation induced by agricultural practices in two case studies with different hydrogeological settings and agricultural activities. Both study areas are located in the south of Portugal and clearly show the impact of irrigated agriculture on groundwater quality, as reported by several authors (e.g. Almeida and Silva 1987; Stigter et al. 1998; Stigter and Carvalho Dill 2001a, 2001b). However, there are distinct spatial variations in the degree of contamination. The primary goals to be achieved by the present study were: (1) to create an intrinsic and a specific vulnerability map for each of the study areas based on existing data and new data gathered by the first author in field campaigns; (2) to compare the obtained results with the present-day spatial distribution of nitrate concentrations in the upper aquifers and (3) to discuss the observed similarities and discrepancies between the intrinsic and specific vulnerability and nitrate contamination maps.

The intrinsic method applied in the case studies was DRASTIC, a parametric system method developed by Aller et al. (1987) for the U.S. Environmental Protection Agency (EPA). It is one of the most widely used groundwater vulnerability assessment methods, with applications in countries such as the United States (Rupert 2001), Sweden (Rosen 1994), South Korea (Kim and Hamm 1999), South Africa (Lynch et al. 1997) and Por-

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Fig. 1 Location of the study areas (indicated by the *dashed rectangles*)

tugal (Lobo-Ferreira and Oliveira 1993), among many others. The specific vulnerability assessment method, named Susceptibility Index (SI) (Ribeiro 2000), is an adaptation of the DRASTIC method and was developed with the intention of evaluating aquifer vulnerability to diffuse agricultural pollution. Since then it was applied to several case studies in Portugal (Francés et al. 2001; Stigter et al. 2002a, 2002b; Lobo-Ferreira and Oliveira 2003; Ribeiro et al. 2003).

Description of study areas

Climate

The study areas named ‘Campina de Faro’ and ‘Campina da Luz’ are located in the Algarve, the southernmost province of Portugal, as indicated in Fig. 1. They are bordered by rivers in the east and west and by the Atlantic Ocean (Ria Formosa lagoon) in the south. The northern limit roughly marks the end of intensive agricultural practices. The areas are characterised by a warm Mediterranean climate with a mean annual air temperature and precipitation, measured at Faro airport, of 17.3 °C (Silva 1988) and 531 mm (Loureiro and Coutinho 1995), respectively. The topographically higher areas more to the north of the study areas receive higher amounts of rainfall caused by the orographic effect. Real evapotranspiration losses are estimated at being between 75 and 88% of the precipitation depending on the method of determination (Silva 1984; Silva 1988; Stigter et al. 1998; De Bruin 1999).

Hydrogeology

Detailed descriptions of the geology of the region including the two study areas are given by Silva (1984) and Silva (1988). In terms of regional hydrogeology, the Instituto Nacional de Água (INAG) defined and characterised 17 aquifer systems built up from carbonate rocks and detritic sediments in the Algarve (Almeida et al. 2000). The local hydrogeology of Campina de Faro and Campina da Luz was studied in more detail by Van Ooijen et al. (1996) and Bonte (1999), respectively.

Figure 2 displays a hydrogeological map of Campina de Faro. Three aquifers are discerned. The oldest aquifer system is formed by south-dipping Cretaceous limestone layers separated by marls. This formation crops out in the north and is found near the city of Faro at depths below 200 m. The overlying aquifer is built up from sub-horizontal Miocene fossil-rich sandy limestones deposited in a graben-like structure bordered by large N–S trending faults. Their thickness increases from north to south and exceeds 200 m near the coast. They are covered by fine sands deposited in the same structure during the Miocene. Together with the overlying sands and gravels of Plio-Quaternary age, these build up the upper aquifer system in the centre and south, with an average thickness of 50 m. Fluvial and marine erosion during the Holocene was followed by the deposition of a thin layer of silts and clays in large parts of the study area, which however do not confer a confined character to the underlying aquifer. A local outcrop of Jurassic gypsiferous material near Faro is related to diapiric activity (updoming) that is also believed to be the origin of the topographical elevation in this area.

The hydrogeological map of Campina da Luz is shown in Fig. 3. The oldest sediments that crop out in the area, which are subdivided into four units, were deposited in the Jurassic (Bonte 1999; Stigter and Carvalho Dill 2001b). The first two and the last units constitute the main aquifers of the region, both exceeding 500 m in thickness, and consist of limestones and dolomites. The third unit, which has a thickness of 450 m and forms an aquitard, is mainly made up of marls. Another aquitard is largely made up of sandy marls of Cretaceous age and crops out in a large area in the southwest, uplifted by the NW–SE trending faults. Miocene sediments cover the Cretaceous and Jurassic units in the centre of the area, where they form an upper aquifer with a 75-m-estimated thickness. Although rather heterogeneous, the main lithology seems to be sandy limestones. Sands and gravels of Plio-Quaternary age have local outcrops in the centre and along the coast. Their thickness does not exceed 20 m. The presence of Holocene silts and clays is restricted to river valleys, while Holocene sands are restricted to the barrier island of Tavira (Ilha de Tavira).

The general direction of groundwater flow is from north to south. Recharge mainly occurs (in the) north of the areas where karstified limestones of Jurassic age crop out. Hydraulic head measurements and analysed groundwater chemistry provided indications of the hydraulic behaviour of some of the faults in the area; the ones trending N–S form preferential flow paths, whereas NW–SE trending faults obstruct groundwater flow, causing steeper hydraulic gradients (Stigter et al. 1998; Bonte 1999).

Land use

Agriculture has been a major form of land use in the areas for centuries. Initially dominated by almond, fig, olive and carob trees and grape yards, agriculture became more intensive with the introduction of irrigation at the end of the 19th century. Nowadays, citriculture is the dominant land use in both areas, though horticulture, both in

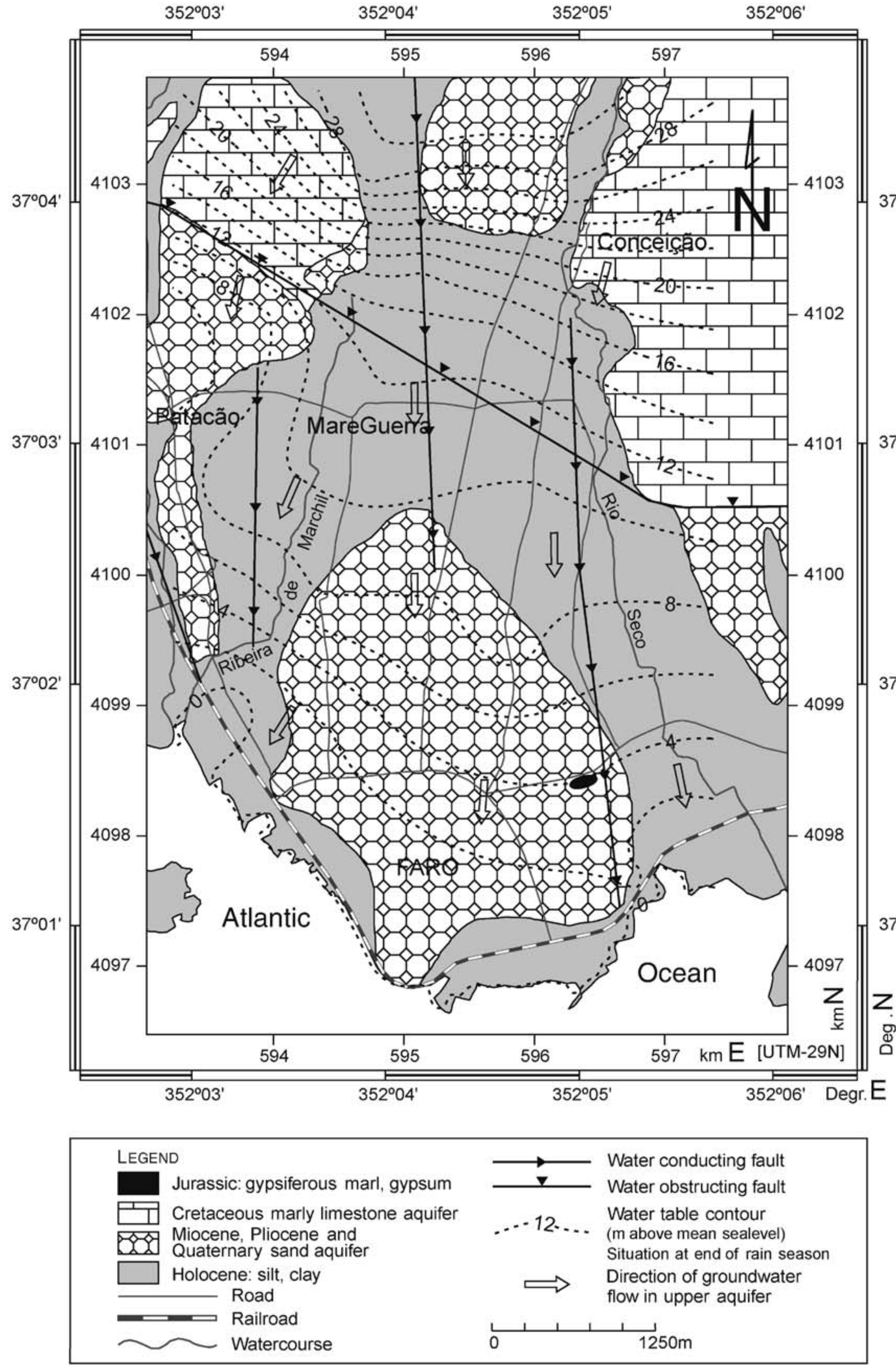

Fig. 2 Hydrogeological map of Campina de Faro

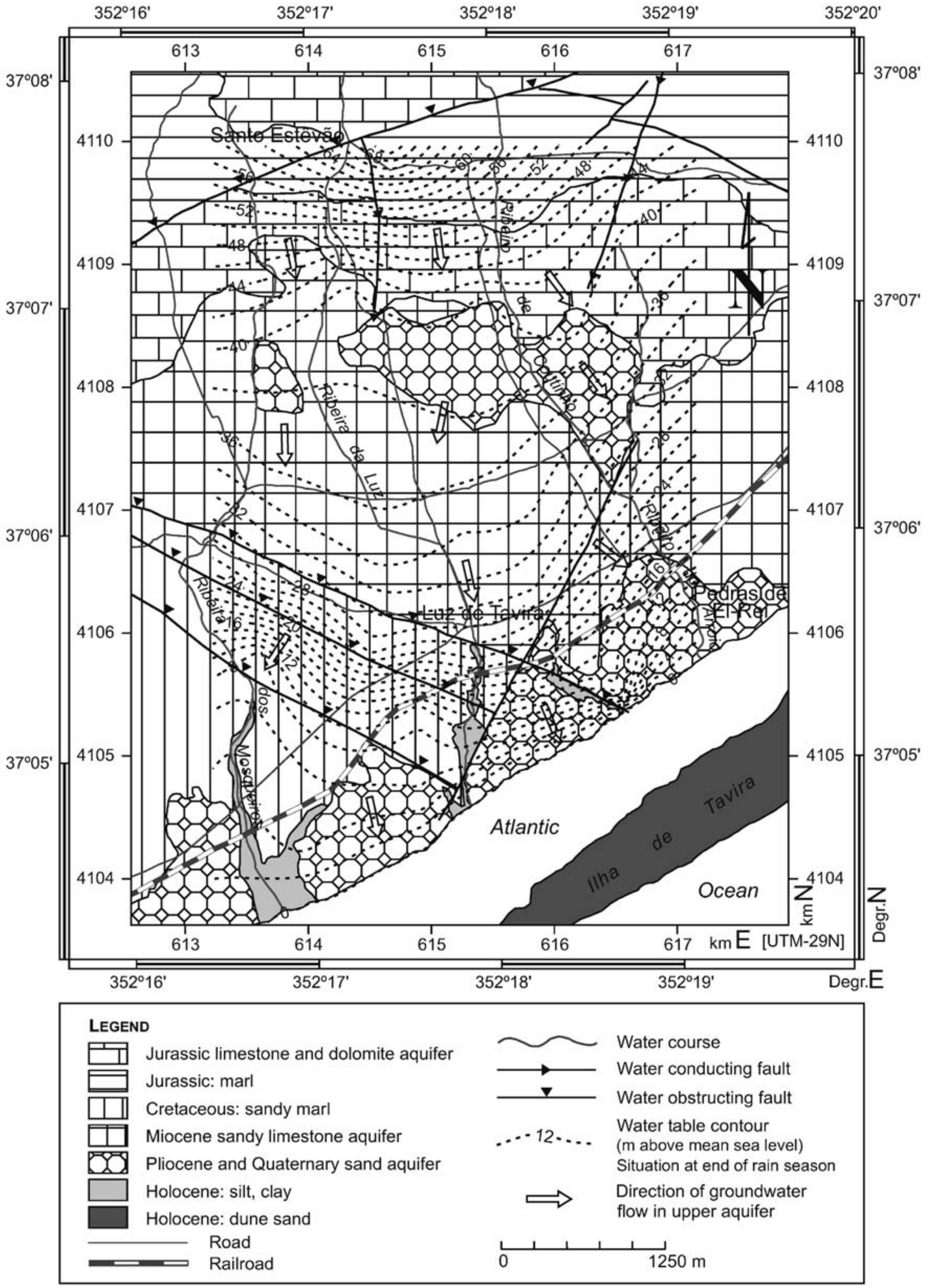

Fig. 3 Hydrogeological map of Campina da Luz (geology adapted from Bonte 1999)

greenhouses and open-air, is also of large importance in Campina de Faro. These cultures require large amounts of water, fertilisers and pesticides in order to obtain high yields. In terms of nitrogen (N), an amount of 150–300 kg/ha. yr is recommended for citrus trees, whereas for crops such as tomatoes and melons (both cultivated in Campina de Faro), quantities are considered per crop cycle (± half a year) and equal 150–200 kg/ha and 50–

Table 1 Definition and weights of the DRASTIC and SI parameters

Letter	Meaning	Weight	Pesticide weight	SI weight
D	Depth to water	5	5	0.186
R	Net recharge	4	4	0.212
A	Aquifer media	3	3	0.259
S	Soil media	2	5	-
T	Topography	1	3	0.121
I	Impact of the vadose zone media	5	4	-
C	Hydraulic conductivity of the aquifer	3	2	-
LU	Land use	-	-	0.222

100 kg/ha, respectively (Quelhas dos Santos 1991). As for water demand, the Instituto de Desenvolvimento Rural e Hidráulica (IDRHa) indicates 770 mm for citriculture and 440 mm and 400 mm per crop cycle for tomatoes and melons, respectively. More details on land use will be given in the section on the application of the vulnerability indices.

Nitrate vulnerable zones

The study area of Campina de Faro is inserted in one of the five areas currently classified as Nitrate vulnerable zones (NVZs) by Portuguese legislation, in compliance with the European Union Nitrate Directive 91/676/EEC concerning the protection of waters against pollution caused by nitrates from agricultural sources. Not satisfied by the low number of NVZs in Portugal, the European Commission has requested the designation of more areas. In the meantime, new areas, including Campina da Luz, have been studied and proposed for NVZ designation by INAG.

Description of DRASTIC and the Susceptibility Index

DRASTIC was developed by Aller et al. (1987) for the US EPA, with the purpose of creating a methodology that would permit a systematic evaluation of the groundwater pollution potential of any hydrogeological setting. The seven hydrogeological factors that form the acronym DRASTIC are defined in Table 1. Each factor is subdivided into ranges or significant media types that are rated between 1 and 10 according to their relative impact on the pollution potential, as indicated in Table 2. The final index is obtained by the weighted sum of the factors, different weights being assigned in the assessment of the pesticide contamination potential (Table 1). Values range from 23 to 226 (highest vulnerability) and are distributed among eight classes. The DRASTIC index can be calculated for various hydrogeological settings and subsequently mapped. The most important assumptions made when assessing vulnerability with DRASTIC (Aller et al. 1987) are that the contaminant is introduced at the ground surface, flushed into the groundwater by precipitation and has the mobility of water. To get an idea of the influence of each of the hydrological factors on the final index,

Table 2 Ranges (left columns) and ratings (right columns) of the DRASTIC parameters

D[a] (m)		R[a] (mm)		T[a] (%)		S		C (m/day)	
<1.5	10	<51	1	<2	10	Thin or Absent	10	<4.1	1
1.5–4.6	9	51–102	3	2–6	9	Gravel	10	4.1–12.2	2
4.6–9.1	7	102–178	6	6–12	5	Sand	9	12.2–28.5	4
9.1–15.2	5	178–254	8	12–18	3	Peat	8	28.5–40.7	6
15.2–22.9	3	>254	9	>18	1	Shrinking and/or aggregated clay	7	40.7–81.5	8
22.9–30.5	2					Sandy loam	6	>81.5	10
>30.5	1					Loam	5		
						Silty loam	4		
						Clay loam	3		
						Muck	2		
						Non-shrinking and non-aggregated clay	1		

A[ab]		I[b]	
Massive shale	1–3 (2)	Confining layer	1
Metamorphic/igneous	2–5 (3)	Silt/clay	2–6 (3)
Weathered metamorphic/igneous	3–5 (4)	Shale	2–6 (3)
Glacial till	4–6 (5)	Limestone	2–5 (3)
Bedded sandstone, limestone and shale sequences	5–9 (6)	Sandstone	2–7 (6)
Massive sandstone	4–9 (6)	Bedded limestone, sandstone, shale	4–8 (6)
Massive limestone	4–9 (8)	Sand and gravel with significant silt and clay	4–8 (6)
Sand and gravel	4–9 (8)	Sand and gravel	4–8 (8)
Basalt	2–10 (9)	Basalt	2–10 (9)
Karst limestone	9–10 (10)	Karst limestone	8–10 (10)

[a] For SI the ratings are multiplied by 10

[b] Typical ratings between brackets

DRASTIC considers the following conditions as contributing to a high pollution potential:

- Shallow depth to groundwater (D), related to a short travel time of the contaminant in the unsaturated zone and hence little chance for attenuation (for instance through oxidation or interaction with the surrounding media)
- High net aquifer recharge (R), the principal vehicle for leaching contaminants to the aquifer
- Permeable aquifer media (A) showing no reactivity with regard to the contaminant, thus allowing a quick spreading through the aquifer
- Soil media (S) lacking (non-shrinking and non-aggregated) clay and organic material, conferring a low attenuation capacity and increasing the mobility of the contaminant
- Flat topography (T), decreasing the likelihood of surface runoff and erosion and hence facilitating infiltration
- Permeable vadose (unsaturated) zone media (I) showing no reactivity with regard to the contaminant, thus creating conditions for leaching towards the aquifer
- High hydraulic conductivity of the aquifer (C), allowing quick spreading throughout the aquifer (though this also depends on hydraulic gradient)

The Susceptibility Index (SI), an adaptation of the DRASTIC method, was developed with the intention of evaluating aquifer vulnerability on a large to medium scale, 1:50000–1:200000 (Ribeiro 2000), with respect to diffuse agricultural pollution in hydrogeological settings typically found in Portugal. The main difference is the addition of a parameter defining land cover, thus abandoning the concept of a purely intrinsic vulnerability assessment method. The index name is in harmony with the definition of susceptibility, i.e. the lack of ability to resist the impact of contaminants on the quality of groundwater, provided by Vrba and Zoporozec (1994). The principal types of land use and their assigned ratings provided by a team of Portuguese scientists (Ribeiro 2000) are shown in Table 3.

Three DRASTIC parameters were deliberately left out of the construction of the Susceptibility Index. Two of these include the soil (S) and unsaturated zones (I), thus suggesting that their direct influence on the contamination linked to agricultural practices is of little importance. According to Francés et al. (2001), soil type is indirectly represented by land use, hereby referring to Foster (1987). However, many authors, including Foster (1987) and Vrba and Zoporozec (1994), recognize that the soil can have a large attenuation potential, especially when rich in clay minerals and organic matter. In other words, leaving the soil properties out of the vulnerability assessment is not necessarily an obvious choice. On the other hand, an additional justification can be given by the fact that, due to ploughing, tillage and many other techniques applied to improve the soil structure and fertility, the natural soils are frequently disturbed during cultivation of land so that they lose much of their original characteristics.

Table 3 Rating of land cover according to IGP map

Land use	Rating
Agricultural areas	
Irrigation perimeters (annual crops), paddy fields	90
Permanent crops (orchards, vine yards)	70
Heterogeneous agricultural areas	50
Pastures and agro-forested areas	50
Artificial areas	
Industrial waste discharges, landfills	100
Quarries, shipyards, open-air mines	80
Continuous urban areas, airports, harbours, (rail)roads, areas with industrial or commercial activity, laid out green spaces	75
Discontinuous urban areas	70
Natural areas	
Aquatic environments (salt marshes, salinas, intertidal zones)	50
Forests and semi-natural zones	0
Water bodies	0

The unsaturated zone can also have a high attenuation capacity and prevent leaching of the contaminant to the groundwater. In the case of persistent and mobile contaminants, however, its role is merely one of introducing a time-lag, because attenuation is insignificant (Foster 1987). Nitrate is extremely mobile as it does not form insoluble minerals that could precipitate and it is not adsorbed significantly under aquifer conditions (Appelo and Postma 1994). Only in anaerobic conditions and in the presence of organic matter (or any other reduction potential containing material) can denitrification take place.

The last DRASTIC parameter not incorporated in the SI is the hydraulic conductivity of the aquifer (C). This parameter is extremely difficult to evaluate spatially and there are rarely enough data to provide an accurate picture. Moreover, hydraulic conductivity is already qualitatively represented by the aquifer media (A), resulting in an excessive weight of this factor in comparison with the others.

The weight string for the SI was also determined by the team of Portuguese scientists (Ribeiro 2000) and is indicated in Table 1. Since the weights add up to one and the ratings range from 0 to 100 (for the adopted DRASTIC parameters, the ratings were multiplied by 10, see Table 2), the final index also varies between 0 and 100.

Application to the study areas

Both study areas have been subject to a DRASTIC vulnerability assessment before: first on a country scale, 1:500,000 (Lobo-Ferreira and Oliveira 1993) and later on a regional scale, 1:100,000 (Lobo-Ferreira et al. 1995). The application of DRASTIC to the southern part of the

Table 4 Data sources of DRASTIC and SI parameters

Param.	Data source
D	Monthly monitoring of 32 shallow wells between 1997 and 1999
R	Precipitation: DRAOT-Alg[a], FERN[b]; Evapotranspiration: Silva (1984); Silva (1988); Stigter et al. (1998); De Bruin (1999). Crop type: IGP[c]; Irrigation water requirements: IDRHa[d]; Irrigation efficiency: Beltrão (1985); Keller and Bliesner (2000)
A	Geological information: Silva (1984); Silva (1988); Stigter et al. (1998); Bonte (1999), analysis of water table time series
S	Soil maps (scale 1:25,000): IDRHa[d]; soil characteristics: Kopp et al. (1989)
T	Topographical maps (scale 1:25,000, elevation contour interval 10 m): IGeoE[e]
I	Geological information: Silva (1984); Silva (1988); Stigter et al. (1998); Bonte (1999), analysis of water table time series
C	Pumping tests: DRAOT[a], Silva (1988); Tables relating hydraulic conductivities to aquifer lithology: Davis (1969), Freeze and Cherry (1979)
LU	Land cover maps (scale 1:25,000): IGP[c]; aerial photographs: IGP[c]

[a] Direcção Regional do Ambiente e Ordenamento do Território do Algarve
[b] Faculdade de Engenharia de Recursos Naturais, Universidade do Algarve
[c] Instituto Geográfico Português
[d] Instituto de Desenvolvimento Rural e Hidráulica
[e] Instituto Geográfico do Exército

study area of Campina de Faro was presented by Oliveira and Lobo-Ferreira (1998). More detailed studies involving the hydrogeology of the two study areas, in which the first author has always been directly involved, have been carried out since 1996. The results were reported in the works of Stigter et al. (1998), Bonte (1999), De Bruin (1999) and Stigter and Carvalho Dill (2001b). The current applications of DRASTIC and SI are based on this new information as well as existing data. Table 4 gives an overview of the data sources used for each parameter, which will be briefly characterised in the following subsections.

Depth of water (D)

Since the upper aquifers in both study areas can all be considered phreatic (Stigter et al. 1998; Bonte 1999), this parameter is quantified as the depth of the water table beneath the surface. In the period between 1997 and 1999, groundwater levels of the upper aquifers were monitored on a monthly basis in more than thirty shallow wells in each study area (Stigter and Carvalho Dill 2001b). The water levels registered in March 1998 were used to create a piezometric surface, because they were among the highest levels recorded and thus represent the maximum thickness of the aquifer. The coastline was included as an equipotential (0 m). The obtained water table contours are displayed in the hydrogeological maps of Figs. 2 and 3. Using a GIS, the piezometric surface was then subtracted from the topographic surface to obtain the map of water table depths, which was then converted to the map of DRASTIC ratings on the basis of the defined ranges (Table 2). The final maps are shown in Fig. 4. The smallest depths to groundwater are found in the topographically flat parts in the centre of both study areas. Below the hill of Faro and in the north of Campina da Luz depths increase drastically and at some points even exceed 30 m. Intermediate values are found below the smaller hills in the south of Campina da Luz and in the Cretaceous sediments in the north of Campina de Faro. No groundwater levels measurements were carried out beyond the areas' borders.

Net recharge (R)

Net natural recharge, defined as the fraction of rainfall that can infiltrate and reach the aquifers, was determined on the basis of the spatial distribution of rainfall in the study areas and the fraction of evapotranspiration. Surface runoff can be considered insignificant in the study areas. Based on the various estimates of evapotranspiration provided by Silva (1984); Silva (1988); Stigter et al. (1998) and De Bruin (1999), an average value of 20% of the precipitation was used for net recharge. Outcrops of karstified limestones and the city of Faro make up two exceptions. In the first case, a value of 40% was adopted, indicated by Silva (1988) as an average value for these type of rocks in the region. In the second case, the mostly impermeable surface and artificial drainage system of the city cause the aquifer recharge to be extremely low, therefore the lowest range defined by DRASTIC was chosen.

According to Aller et al. (1987), all sources of recharge, including artificial ones, should be considered when choosing an appropriate range for DRASTIC. This seems somewhat odd, as the method is supposed to be intrinsic and not account for any anthropogenic influences. However, in semi-arid and arid regions where effective precipitation is low, irrigation return flow can be an important component of recharge (e.g. Rupert 2001). Though the source of irrigation is local groundwater—causing, in fact, a depletion of the aquifers—return flow is considered as recharge here, because it increases the amount of water percolating through the soil and vadose zone, thereby leaching the contaminants. This increase depends mainly on crop water requirements and irrigation efficiencies. The spatial distribution of crop types in the study areas was determined by the combined use of detailed land cover maps (scale 1:25000) from 1990/1991 and aerial photographs from 1995, both provided by the Instituto Geográfico Português (IGP). Typical values of water requirements for each crop in consideration of the regional climate were available at IDRHa. Since drip irrigation is the most commonly applied irrigation technique in both study areas, irrigation return flow was es-

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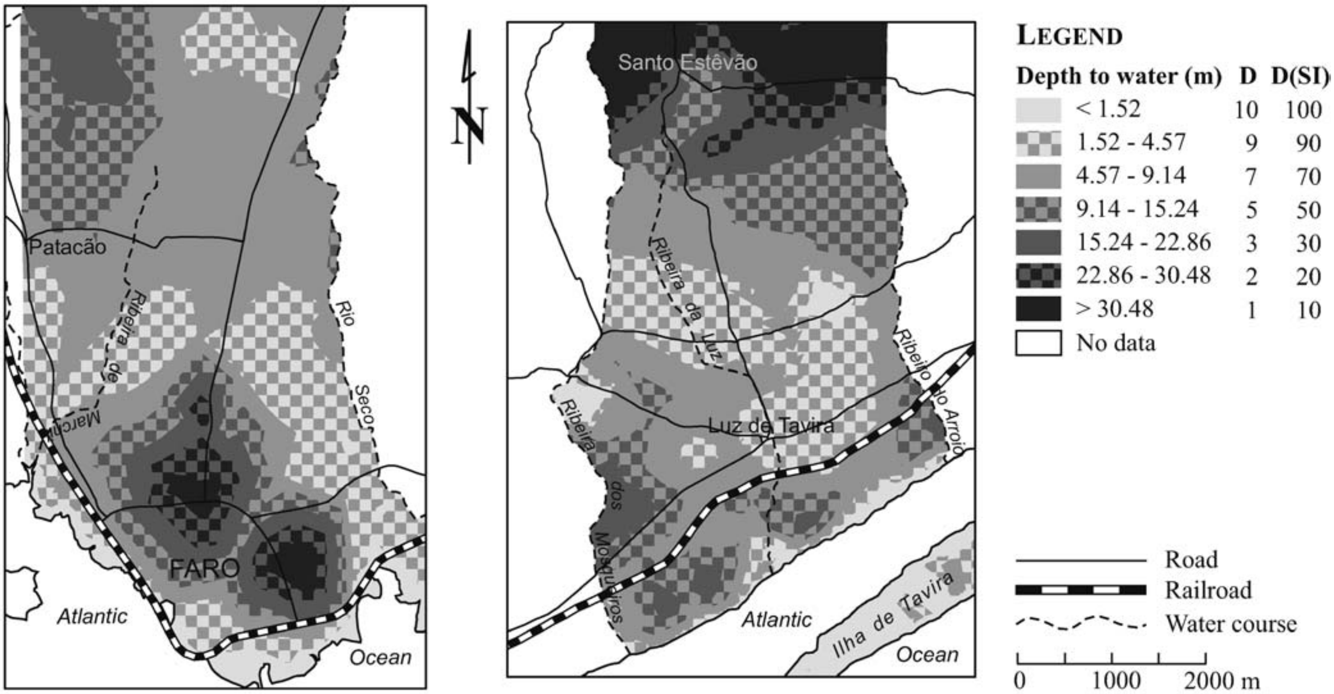

Fig. 4 Depth to water ranges and corresponding ratings according to DRASTIC and SI, in Campina de Faro (*left*) and Campina da Luz (*right*)

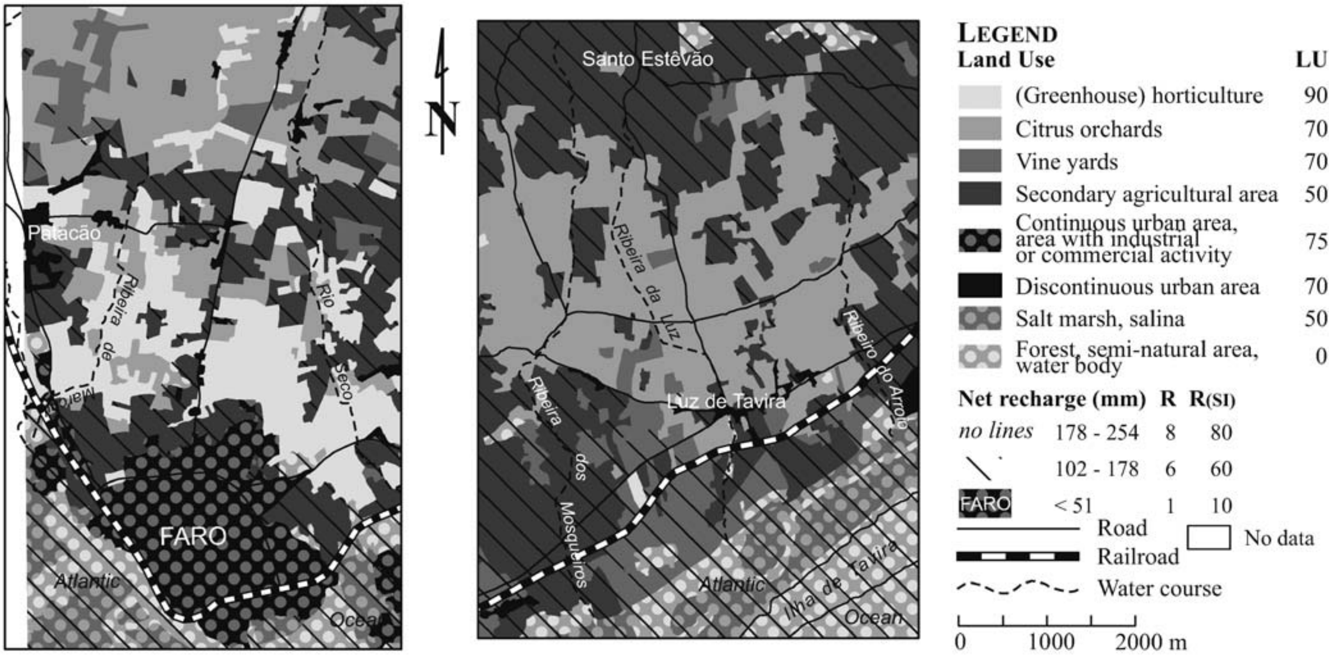

Fig. 5 Land use and net recharge ranges (*superimposed*) and corresponding ratings according to DRASTIC and SI, in Campina de Faro (*left*) and Campina da Luz (*right*)

timated as 10% of the applied water quantities (Beltrão 1985; Keller and Bliesner 2000).

After creating maps of both natural and artificial recharge, they were added in a GIS and the resulting values were transformed on the basis of the defined ranges (Table 2) to obtain the final rating maps shown in Fig. 5. The increase of recharge fed by irrigation return flow is clearly visible, as in most irrigated areas the assigned rating is 8, indicating a recharge between 176 and 254 mm. The non-agricultural areas having only received between 102 and 176 mm supplied from precipitation, were thus assigned a rating of 6. The only two exceptions

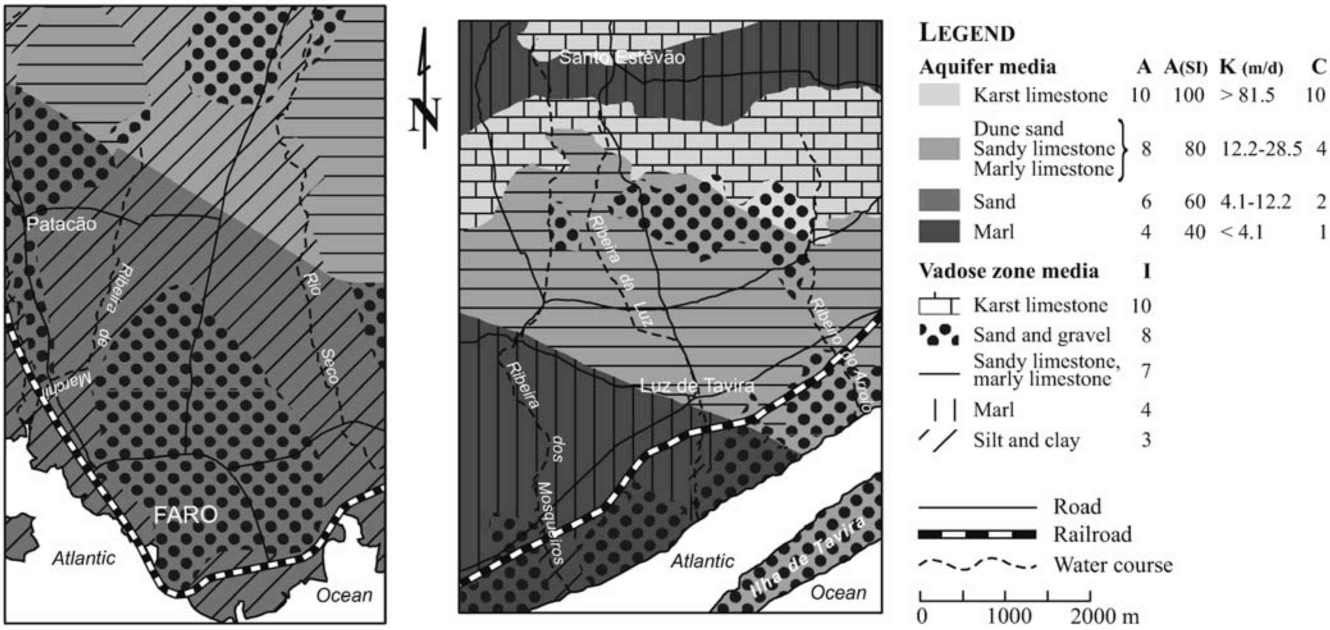

Fig. 6 Aquifer media (*grey tones*), vadose zone media (*superimposed symbols*) and hydraulic conductivities ranges and corresponding ratings according to DRASTIC and SI, in Campina de Faro (*left*) and Campina da Luz (*right*)

are the limestone outcrops (higher natural recharge, rating 8) and the city of Faro (recharge lower than 51 mm, rating 1).

Aquifer media (A) and hydraulic conductivity (C)

The parameters A and C are discussed together in this subsection, as they are closely related. The hydrogeological maps of the study areas and their descriptions already gave an overview of the aquifers present in the study area. The final maps obtained for these two parameters are different from the hydrogeological maps in that they display the upper aquifers rather than the outcropping formations, as can be observed in Fig. 6. In other words, where outcropping sediments form thin layers covering the aquifer, these are "stripped off", as they play an insignificant role in determining aquifer properties.

Figure 6 indicates the DRASTIC ratings assigned to the aquifer media. Regarding Campina da Luz, the highest rating (10) is assigned to the karstified limestone aquifers in the north, which are extremely permeable due to the presence of large interconnected fractures and cavities. The Miocene aquifer in the centre receives a rating of 8, because, although rather heterogeneous, sandy limestone is the most significant medium and should therefore be considered (Aller et al. 1987). The same rating is assigned to the local sand aquifer of the island "Ilha da Tavira", the typical DRASTIC rating for a sand and gravel aquifer. Marly sediments that make up the Cretaceous aquifer in the south and the Jurassic aquifer in the north receive a rating of 4, as their low permeability allows for a long reaction time and high attenuation capacity. In Campina de Faro, separated by the NW–SE trending fault, only two upper aquifer systems are distinguished (Silva 1988; Stigter et al. 1998). South of the fault, the upper aquifers, built of poorly sorted sands, receives a rating of 6, due to its relatively long groundwater residence (and reaction) time. Towards the north, the sand aquifer quickly disappears, and Miocene sandy limestones and Cretaceous limestone layers separated by marls make up the upper aquifer. These formations are assigned a rating of 8, limestone being the most significant medium.

The parameter regarding hydraulic conductivity of the aquifer is most prone to error, as it has a large spatial variability (especially in limestone aquifers) and data are very scarce. Aller et al. (1987) provide large ranges for this parameter (Table 2) and suggest the use of tables relating hydraulic conductivities to aquifer lithology such as those provided by Davis (1969) and Freeze and Cherry (1979). In the present study, a combination of available data, literature and the referred tables was used to obtain the correct ranges and corresponding ratings for each aquifer, which are also indicated in Fig. 6. Karst limestone aquifers receive a rating of 10, indicating hydraulic conductivities above 81.5 m/d (Lobo-Ferreira et al. 1995). With hydraulic conductivities well below 4 m/d (Silva 1984; Bonte 1999), the marls make very poor aquifers, and thus receive a rating of 1. Rating 2 is assigned to the sandy aquifer in Campina de Faro and rating 4 to all other aquifers.

Soil media (S)

Soil maps with a scale of 1:25000 acquired from IDRHa, were used to determine the spatial distribution of the soil types in the study areas. The work of Kopp et al. (1989) was consulted when selecting the appropriate soil media, which was done following the approach suggested by Aller et al. (1987). A short description of the main soil

Table 5 Description of principal soil classes present in the study area

Code	Description	Soil media	Rating
A. Soc.	City, village	No soil	1
Vcd	Argilic, little unsaturated soil—red or yellow Mediterranean soil, derived from compact limestones or dolomites	Clay[a]	1
Aac	Incipient soil: modern alluvial soil, calcareous, with heavy texture	Clay[a]	1
Assa	Halomorphic soil: saline soil, of high salinity, derived from alluvium, with heavy texture	Clay loam	3
Atac	Incipient soil: ancient alluvial soil, calcareous, with heavy texture	Clay loam	3
Ps	Hydromorphic soil, with eluvial horizon, planosol, derived from consolidated sands, argilic conglomerates or clays	Clay loam	3
Vc	Red calcareous soil, derived from limestones, under climate of xeric regime	Clay loam	3
Vtc	Argilic, little unsaturated soil: red or yellow Mediterranean soil, derived from other consolidated sands	Clay loam	3
Pc	Grey calcareous soil, derived from non-compacted limestones, under climate of xeric regime	Loam	5
Vt	Litholic soil, non-humic, little unsaturated, derived from coarse consolidated sands	Sandy loam	6
Rg	Incipient soil: psamitic regosol, non-humid	Sand	9
Arc	Rock outcrop of limestones or dolomites	Thin or absent	10

[a] Non-shrinking and non-aggregated

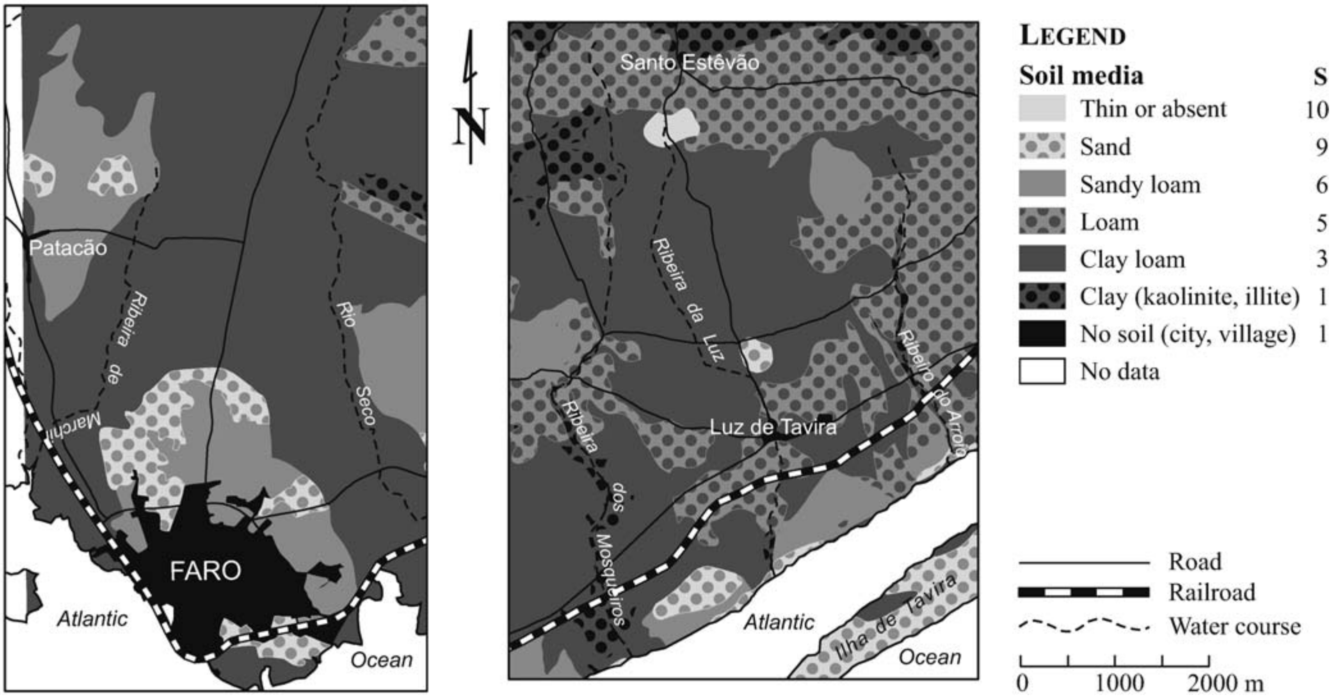

Fig. 7 Soil media and corresponding ratings according to DRASTIC, in Campina de Faro (*left*) and Campina da Luz (*right*)

classes found in the study areas is given in Table 5 and the selected soil media and corresponding ratings are mapped in Fig. 7. The most widely present soil medium is clay loam (with rating 3), developed in the Holocene silts and clays in Campina de Faro and from major parts of the Cretaceous marls and Miocene sandy limestones in Campina da Luz. Where Holocene and Plio-Quaternary sands have been deposited, the derived soil media are mainly sandy loam (rating 6) and sand (rating 9). The areas in Campina da Luz with karstified limestones either correspond to soils with high amounts of clay (Vcd) or to areas where rock outcrops exist and soil is absent (Arc). In the former case, the assigned rating is 1, as the clays are mostly kaolinitic (Kopp et al. 1989), whereas in the latter case the highest rating is assigned. Areas occupied by cities or villages lost most of their natural soil which was replaced by all sorts of artificial covers. Though not completely correct, these areas were assigned the lowest possible soil rating, as infiltration of any type of contaminant is strongly inhibited. Assigning a rating permits the calculation of a DRASTIC index and comparison with SI (where the soil parameter is not included) in these areas of anthropogenic influence.

It is likely that the maps shown in Fig. 7 are somewhat different from the present-day spatial distribution of the soil types, because a large part of the land has been cultivated and as a consequence many soils have suffered significant alterations during tillage, through deep or

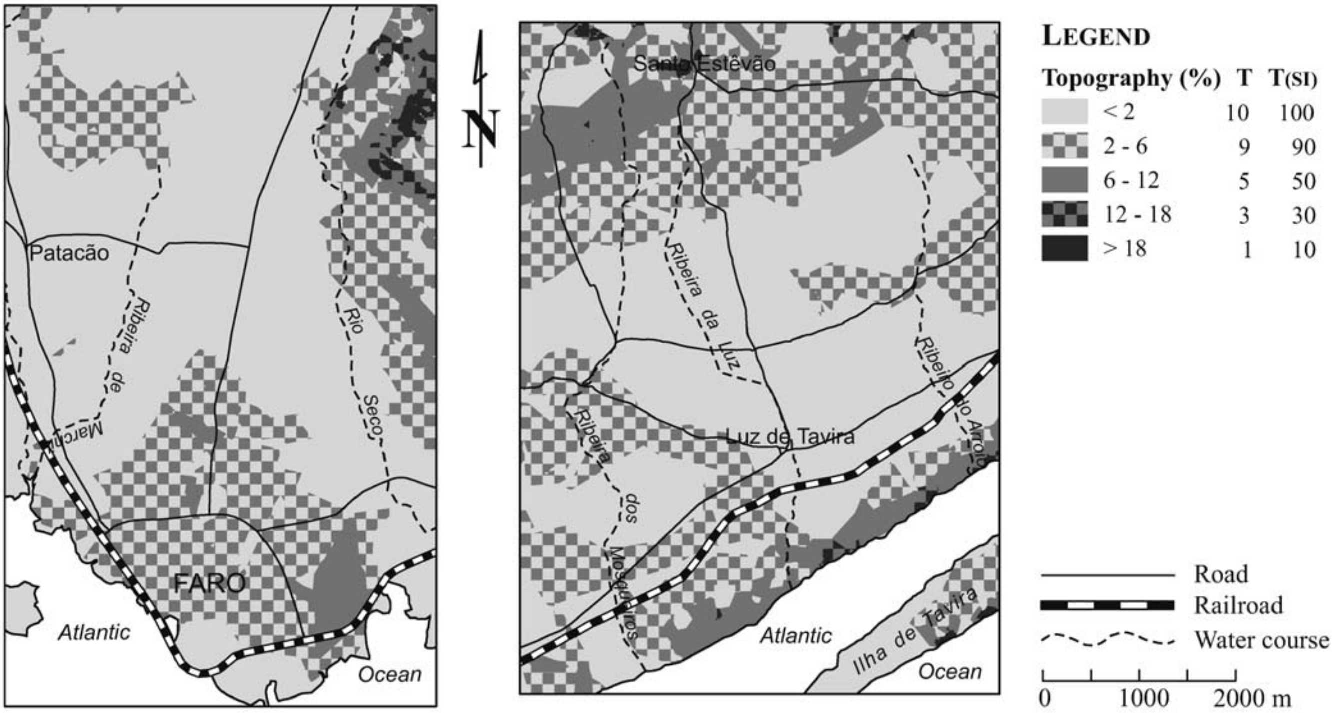

Fig. 8 Topography ranges and corresponding ratings according to DRASTIC and SI, in Campina de Faro (*left*) and Campina da Luz (*right*)

shallow ploughing, destoning, terracing and other soil improvement techniques. Consequently, little or nothing of the original soil profile is preserved.

Topography (T)

Topography, which in this case refers to the percent slope of the land surface, was determined directly from the topographic maps (scale 1:25000). These maps contain elevation contour lines with an interval of 10 m as well as many geodesic vertices that provide useful information about the variability of the topographical surface. The (average) percent slope is obtained by dividing vertical drop by horizontal distance (and multiplying by 100). After calculating and mapping the percent slope values, they were assigned ratings on the basis of the corresponding ranges defined by DRASTIC. Figure 8 shows the resulting parametric map. The central parts of both areas receive the highest ratings, as topography here is very flat (<2%). Slopes between 2 and 6% are found in the largest part of the remaining area.

Impact of the vadose zone media (I)

The upper layers, from which the soils are derived, should usually be considered as the most significant when determining the vadose zone media, although other formations can also interfere when the upper layers are thin and groundwater levels are deep. The latter is generally not the case (Fig. 4), which is why the outcropping formations were used to define the ranges and ratings of this parameter presented in Fig. 6.

Where the unsaturated zone consists of karstified limestone, a rating of 10 is assigned, reflecting the absence of any attenuation potential of the contaminant. The typical rating of 8 is assigned to the Plio-Quaternary sands and gravels and Holocene dune sands. These sediments have a low clay and organic matter content and are relatively permeable, making it easy for a contaminant to percolate through the vadose zone and reach the aquifer without much interference. The marls and especially the Holocene silts and clays form a barrier and can significantly retard a contaminant's movement. The marls receive a rating of 4, while the typical rating of 3 is assigned to the silts and clays. Finally, where the vadose zone is made of sandy or marly limestone, the assigned rating is 7.

Land use (LU)

In order to evaluate the land use parameter of SI, the land cover maps and aerial photographs referred to under the section of recharge were consulted. The aerial photographs are from 1995 and proved very useful for updating the land use data. Figure 5 presents the land cover maps for the study areas. Eight categories are discerned, four of which regard agricultural activity. The highest rating (90) is assigned to horticulture, which occupies a large area in Campina de Faro. A lower rating (70) is assigned to the areas with citriculture, which assumes that their influence on the contamination potential is lower. As was noted when describing the study areas, citriculture (the dominant crop type in both study areas) is also practiced in a very intensive way and perhaps the lower rating is not entirely justified. Moreover, that the other crop types typically present in the Algarve, such as olives, almonds, figs and vine yards, received the same rating, is incorrect when considering the amounts of water and fertiliser recommended for these crop types (Quelhas dos Santos 1991). Vine yards occupy a relevant fraction of the cultivated land in the north of Campina de Faro and in the south of Campina da Luz. Finally, so-called 'secondary' agricultural areas, where agriculture is not intensively practiced, are assigned a rating of 50.

With respect to non-agricultural land cover, the city of Faro and several areas with industrial or commercial activities around the Algarvian capital receive the highest rating (75), whereas discontinuous urban areas such as those belonging to the villages of Luz or Patacão are assigned a slightly lower rating (70). The salinas and salt marshes present in the south (the latter belonging to the Ria Formosa lagoon system) receive a rating of 50. Finally, semi-natural areas, forests and water bodies are considered non-polluting areas and hence the assigned rating is 0.

Calculation and mapping of DRASTIC and SI indices

After mapping all the parameters, the vulnerability maps were obtained by overlaying the individual maps in a GIS and calculating the indices on a fine mesh (grid spacing of 25 m). For each grid cell the two indices were calculated by the weighted sum of the parameters as follows:

$$\mathrm{DRASTIC} = 5 \times D + 4 \times R + 3 \times A + 2 \times C + T + 5 \times I + 3 \times C$$

$$\mathrm{SI} = 0.186 \times D + 0.212 \times R + 0.259 \times A + 0.121 \times T + 0.222 \times LU$$

The values are distributed among eight classes which are attributed a qualitative degree of vulnerability ranging from "extremely low" to "extremely high". The significance of such a high number of classes, also used by Aller et al. (1987), is questionable, but as it enhances spatial resolution, it facilitates the comparison between the obtained vulnerability indices and nitrate contamination levels in the areas. One should bear in mind that absolute values of the indices can not be compared directly, nor do these have any physical meaning.

Creation of nitrate concentration maps

In order to evaluate the results obtained by the vulnerability assessment methods, the nitrate concentrations in groundwater of the upper aquifers were observed. Data were gathered in field campaigns between 1996 and 1999, and consisted of 93 samples analysed at the laboratory of the Vrije Universiteit complemented with 70 qualitative field measurements (NO_3^- strips) in areas lacking the former. In spite of having a larger error, the qualitative field measurements were extremely useful for optimisation, which sought to produce a spatial sample distribution as uniform as possible. Moreover, their values were in good correspondence with the surrounding laboratory samples.

After performing a structural analysis of the spatial distribution of the nitrate concentrations in each study area (based on their experimental semi-variogram) and fitting a spherical theoretical model, the maps were created using an ordinary kriging interpolation algorithm. Eight concentration classes (mg NO_3^-/L) were discerned and attributed a qualitative rating, so as to be analogous to the vulnerability maps. Extremely low (<10 mg/L), very low (10–25 mg/L) and low (25–50 mg/L) contamination levels were defined below the drinking water limit currently known as the parametric value in Portuguese legislation and the EU Directive (98/83/CE) on which it is based.

Results

DRASTIC maps

The DRASTIC maps are presented in Fig. 9. Only seven classes are shown, as the highest class (extremely vulnerable) is not present. The highest indices (180–199) are calculated for some parts of the Jurassic limestone unit in Campina da Luz, which is therefore considered to have very high vulnerability to groundwater contamination, in spite of a clay loam soil medium (Fig. 7) and a fairly thick unsaturated zone (more than 9 m according to Fig. 4). The main causes are the vadose zone and aquifer media made up of karstified limestone (Fig. 5 and Fig. 8), a high recharge caused by irrigation return flow (Fig. 5) and a flat topography (Fig. 8). South of the village of Santo Estêvão, recharge is lower (no irrigation), but there is no soil to attenuate the contaminant. The decrease of vulnerability from 'very high' to 'high' (index 160–179) in the north is due to a deeper groundwater table or the lack of irrigation-fed recharge. 'Moderate to high' vulnerability (index 140–159) is estimated for the limestone unit that has its water table at more than a 30-m depth and is covered by clay soils.

The Jurassic marl unit in the north, regarding vulnerability class levels, is classified as 'low' (index 100–119), 'very low' (index 80–99) and 'extremely low' (index <80), depending mainly on depth to groundwater, recharge and soil type. The lowest vulnerability indices are calculated in areas where clay soils have developed, recharge is less than 178 mm and the vadose zone is more than 30-m thick.

In the centre, the Miocene sandy limestone unit contains large areas with 'high' vulnerability to groundwater contamination. Here, groundwater is near the surface (in some cases at less than 1.5 m depth, see Fig. 4), recharge from irrigation is high and the topography is flat. The vadose zone and aquifer have lower ratings than the karstified limestones, though still quite high (rating of 7). The hydraulic conductivity is also clearly lower, which causes the lowering of the DRASTIC index. Non-irrigated areas and areas where the vadose zone increases in depth

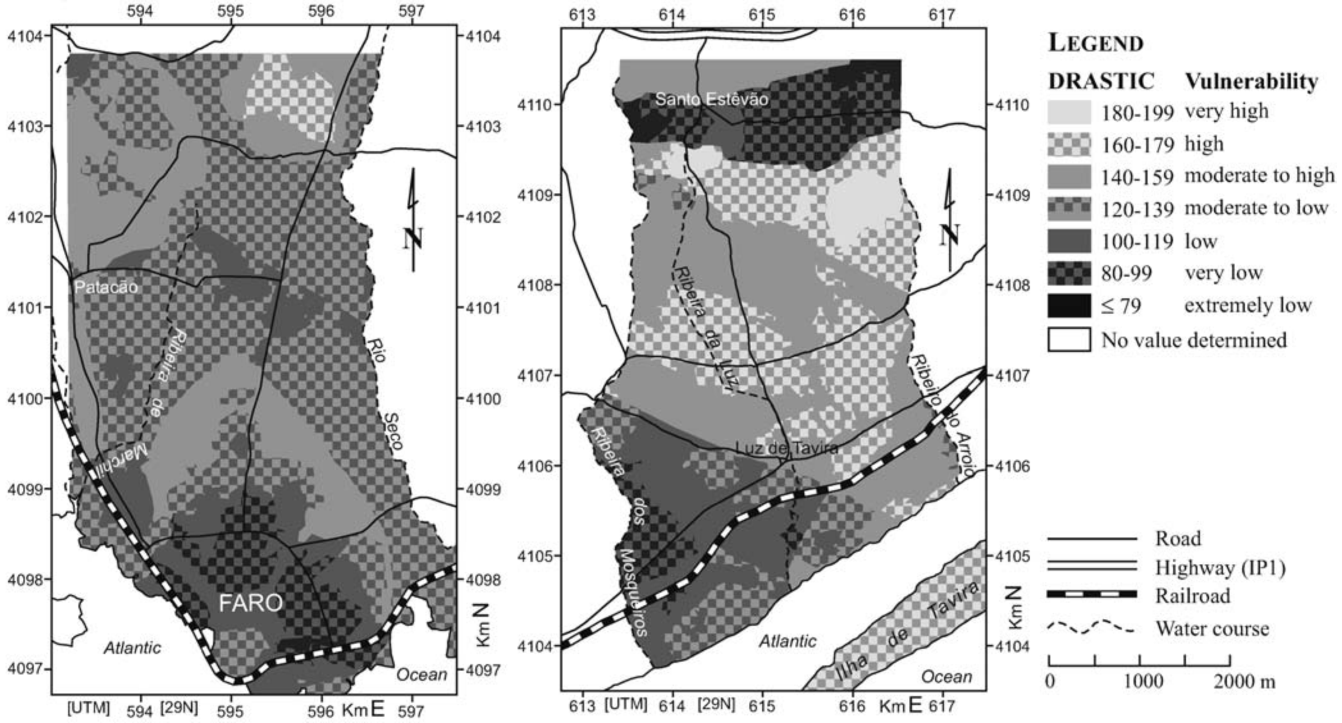

Fig. 9 DRASTIC map of Campina de Faro (*left*) and Campina da Luz (*right*)

have a drop in vulnerability, which classifies them as 'moderate to high'.

More to the southwest, a sudden drop to 'moderate to low' vulnerability (index 120–139) occurs as the aquifer and vadose zone media change to marls in the Cretaceous marl unit below the northernmost NW–SE trending fault (Fig. 3). As groundwater goes deeper below the surface, 'low' and eventually 'very low' vulnerability to groundwater contamination is achieved. Recharge is relatively low and is hardly supplied by irrigation return flow, since agriculture is of little significance in this area, mainly due to the high salinity of groundwater used for irrigation.

The island of Ilha de Tavira has a 'high' vulnerability to contamination since water is near the surface, topography is mostly flat and soil, vadose and aquifer media all have a low contaminant attenuation capacity. Recharge is relatively low as it is only supplied by precipitation.

In Campina de Faro, the two highest vulnerability classes are not represented and the 'high' vulnerability class is restricted to a relatively small area in the northeast located in the Cretaceous limestone unit. High recharge (including irrigation return flow), flat topography and a vadose zone consisting of Plio-Quaternary sand and gravel all contribute to the 'high' vulnerability. On the other hand, the relatively low rating of hydraulic conductivity and soil media (clay loam) prevent higher values of the DRASTIC index. In the neighbouring area, vulnerability decreases to 'moderate to high' as depth to water increases and to 'moderate to low' where the vadose zone medium changes to silt and clay. In the northwest, the vadose zone consists of marly limestone, increasing vulnerability again to 'moderate to high', but when groundwater is found at depths below 15 m, 'moderate to low' vulnerability is assessed.

In the Plio-Quaternary and Miocene sand unit, assessed vulnerability is generally lower. A large part of the area, not taking into account the hill in the south on which Faro was built, either has 'moderate to high' or (more frequently) 'moderate to low' vulnerability. This depends mainly on the vadose zone material being made up of 'sand and gravel' or 'silt and clay', respectively. The apparently higher attenuation capacity of the clay loam soil and the relatively low hydraulic conductivity of the sand aquifer confer on the area its moderate vulnerability, in spite of a flat topography and a high irrigation-fed recharge. Some areas that lack this artificial recharge or that have a water table more than 9 m beneath the surface, have a 'low' estimated vulnerability.

Under the hill of Faro, depth to groundwater increases and slopes are steeper, which reduces the vulnerability. The city itself is a unique 'setting', where natural recharge of the aquifers is almost nil and the 'soil' is impervious. As slopes are also steeper, vulnerability to groundwater contamination here drops to 'low' and 'very low' levels.

SI maps

Before discussing the spatial distribution of the SI indices, it is important to recall the main differences between SI and DRASTIC. The relative weights (r.w.) of the first two parameters (depth to water and recharge) in the final index are comparable, amounting to 22 and 17% in DRASTIC and 19 and 21% in SI, respectively. Aquifer

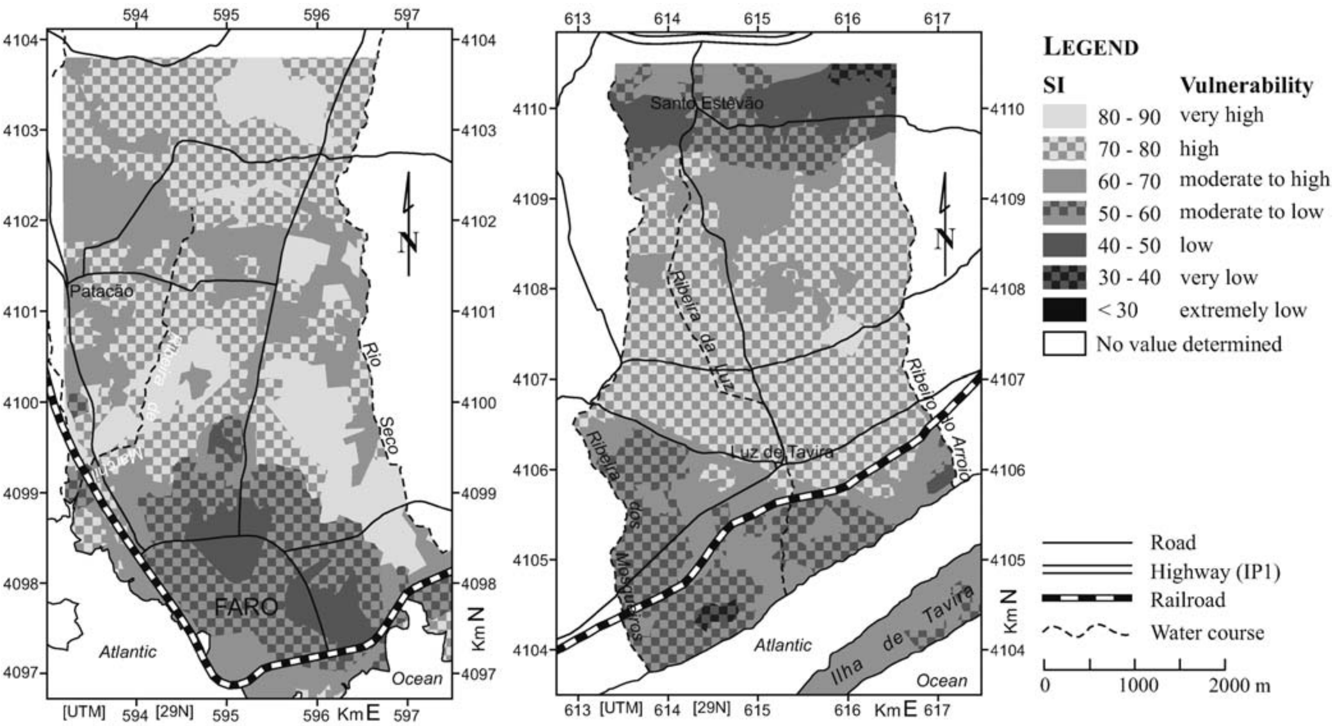

Fig. 10 SI map of Campina de Faro (*left*) and Campina da Luz (*right*)

media (and its attenuation capacity) has twice as much weight in SI (26% r.w.) than in DRASTIC (13% r.w.), but hydraulic conductivity is not considered by SI and has the same weight as aquifer media in DRASTIC. Topography has a bigger influence in SI, namely 12% r.w. against only 4% in DRASTIC. Finally soil media (9% r.w.) and vadose zone media (22% r.w.) are DRASTIC parameters left out by SI, which has incorporated a land use parameter with 22% r.w. In other words, the importance of the hydrological setting is inevitably lower in SI.

The SI maps are presented in Fig. 10. The overall picture is clearly distinct from the one obtained by DRASTIC. The most vulnerable areas are now found in Campina de Faro. A large part of the limestone unit in the north is classified as 'highly' vulnerable (index 70–80) to contamination. Irrigated citriculture is the dominant land use and together with a high recharge contributes to the 'high' vulnerability. Where groundwater is closer to the surface, or where the soil is occupied by intensive horticulture, the limestone unit has 'very high' vulnerability (index 80–90). On the contrary, where slopes are steeper, groundwater is deeper and/or land use is less polluting (e.g. secondary agriculture), vulnerability is reduced to 'moderate to high' (index 60–70).

Regarding the sand aquifer in the centre and south, large parts are classified as 'very highly' and 'highly' vulnerable, very different from the DRASTIC vulnerability assessment. This is mainly due to the existence of intensive agriculture, the higher influence of the flat topography and the fact that SI does not consider soil and vadose zone media. 'Moderate to high' vulnerability areas are related to a deeper water table or a lack of (intensive) agricultural activity. Although the city of Faro is assigned a high rating for land use (75), the deep water table, low recharge and steep slopes provide the area 'moderate to low' and 'low' vulnerability (index 50–60 and 40–50, respectively).

In Campina da Luz, the 'very high' vulnerability areas are practically nonexistent, except for a small spot in the sandy limestone unit where groundwater is almost at the surface. The low incidence of horticulture and the dominance of citriculture contribute to the overall lowering of the indices. Still, a large area is classified as 'highly' vulnerable, and in some cases the calculated indices are at the upper class limit. In the karstified limestone unit in the north, 'high' and 'moderate to high' vulnerability dominates, depending on land use and recharge. The steep slopes and large water table depth in the northernmost parts lower the index to 'moderate to low' and 'low' vulnerability. In the adjacent marl unit, vulnerability is 'moderate to low' in areas with irrigated citriculture and 'low' in the remaining parts, except for a small semi-natural area in the northeast, classified as 'very low' vulnerability (index 30–40).

The sandy limestone unit is almost entirely classified as 'highly' vulnerable, owing to its flat topography, shallow groundwater depths, high recharge and citriculture being the dominant land use. Where not all these conditions are met, vulnerability can be somewhat lower and belong to the 'moderate to low' category. In the southern marl unit, where the only relevant agricultural activity is related to vine yards, vulnerability to pollution

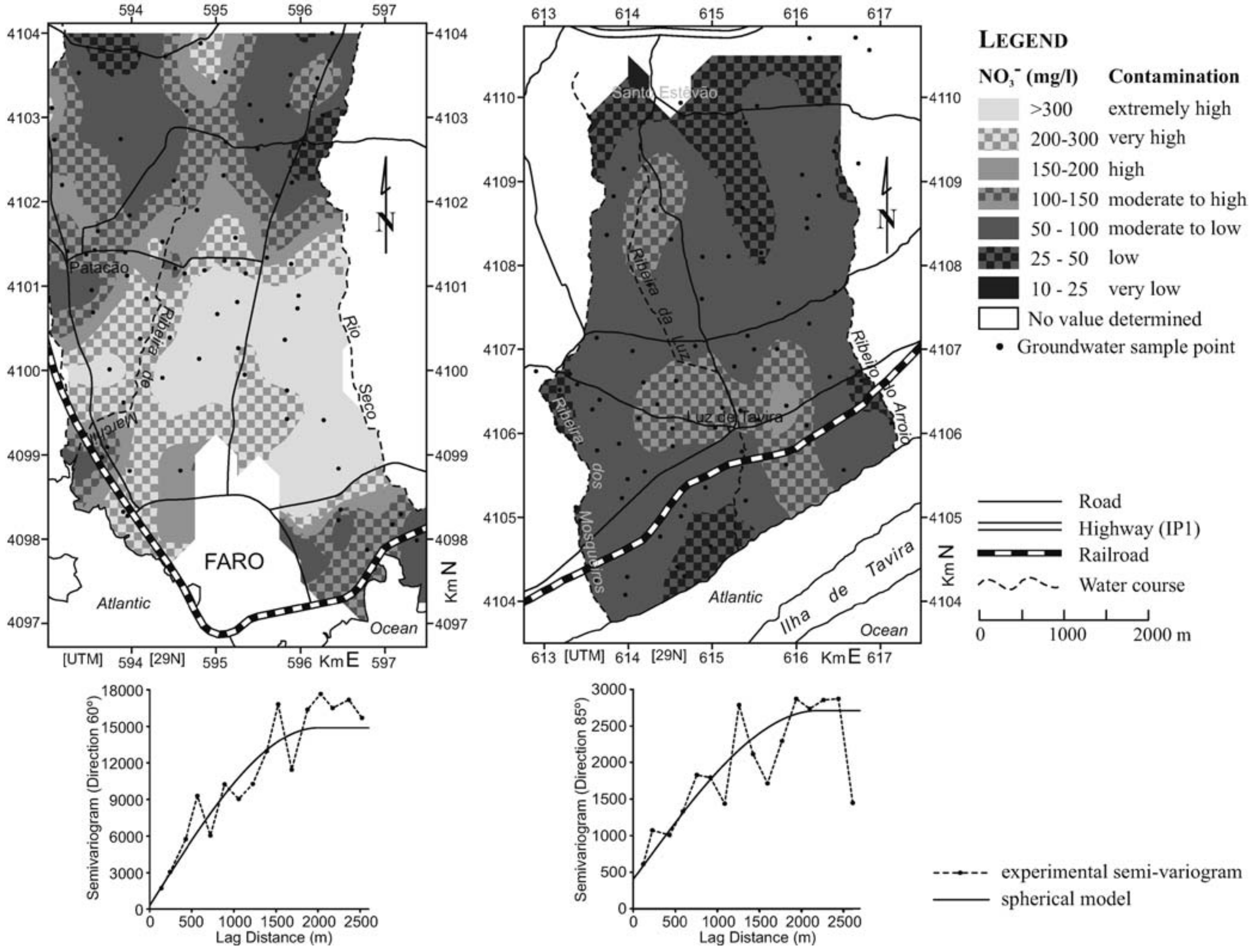

Fig. 11 Nitrate contamination map of Campina de Faro (*left*) and Campina da Luz (*right*), created by ordinary kriging; also shown are the location of the data, their experimental semi-variograms and adjusted spherical models

is ‘moderate to low’ to ‘low’, depending on groundwater depth and topography. The small pine forests on the Plio-Quaternary hills are classified as ‘low’ to ‘very low’ vulnerability zones. The natural environment of the island contributes to a lower assessed vulnerability compared with DRASTIC, though its intrinsic characteristics still provide this unit a ‘moderate to high’ vulnerability.

Nitrate concentration maps

The nitrate contamination maps as well as the corresponding semi-variograms are presented in Fig. 11. Both areas show a good spatial structure in their experimental semi-variogram, with a range of influence of around 2,000 m and a small nugget effect (reflecting a small-scale variability and measurement errors), though somewhat larger in Campina da Luz. The map boundaries correspond to the ones imposed on the vulnerability maps, but some areas are blanked as they lack data and are situated beyond the maximum interpolation search radius. It can immediately be observed that NO_3^- concentrations below the drinking water limit are rarely found in the upper aquifers, and are restricted to a few small areas in the north of Campina de Faro and in the south of Campina da Luz and a somewhat larger area in the north of the latter study area. Whereas groundwater in the largest part of Campina da Luz has nitrate concentrations between 50 and 100 mg/L (moderate to low degree of contamination), in Campina de Faro concentrations frequently exceed 200 and even 300 mg/L (very high to extremely high degree of contamination), especially in the sand aquifer. Intermediate levels are found in both areas.

Discussion

When comparing the vulnerability maps created by the two assessment methods with each other and with the nitrate contamination maps, large discrepancies are found. In order to facilitate the evaluation of the vulnerability assessments, a new set of maps was created by subtracting the assessed vulnerability class from the nitrate contamination class at all locations. Where class difference was

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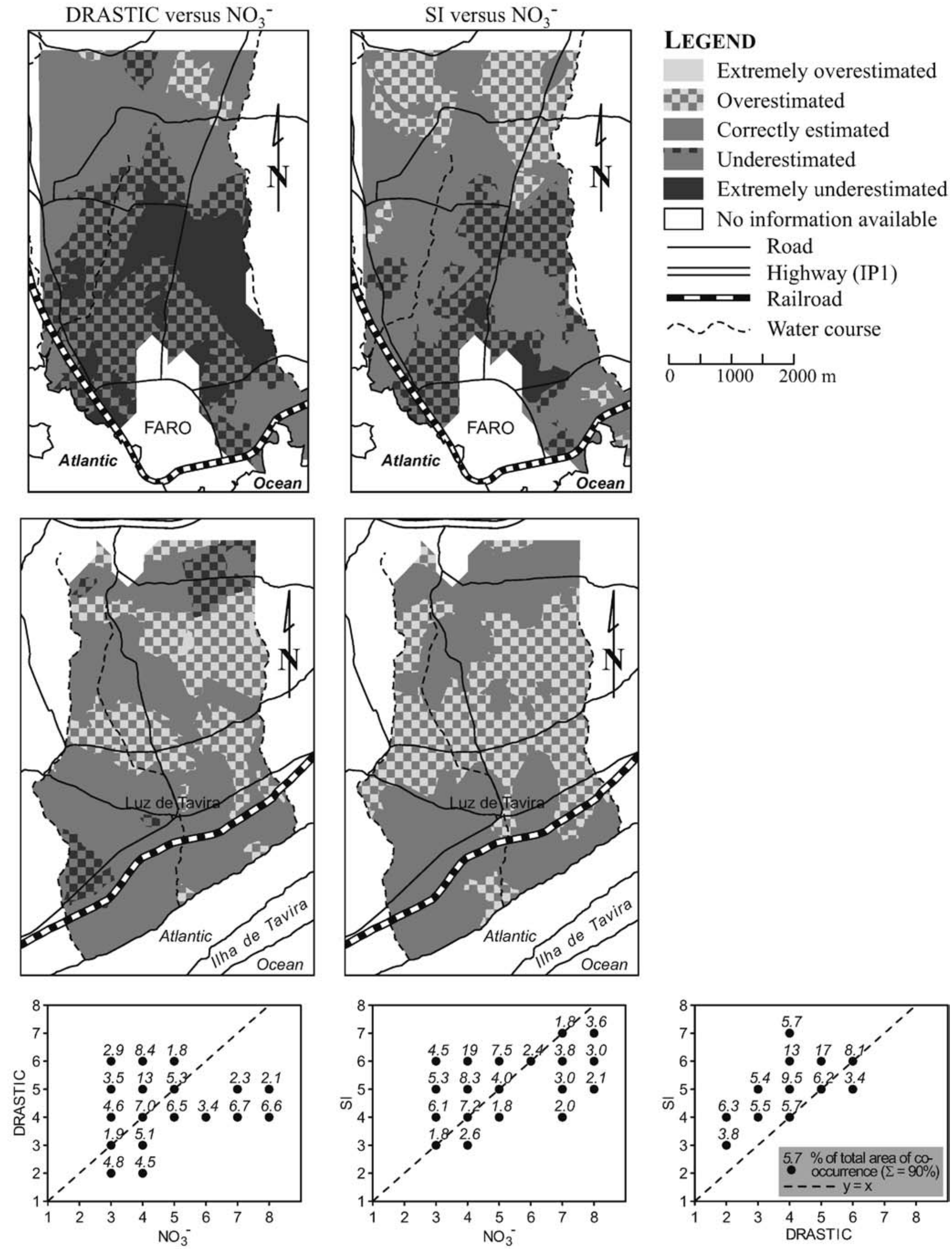
minus one, zero or one (meaning that the vulnerability class is one higher, the same or one lower than that of nitrate contamination), the vulnerability assessment was considered correct. When two or three classes above the nitrate contamination class, the assessed vulnerability was considered overestimated, and the difference was four or five (the maximum difference observed), vulnerability was extremely overestimated. Naturally, the same rules applied to the underestimation of vulnerability. The maps presented in Fig. 12, are quite subjective, as they highly depend on class definition, but they give a good overview of where the DRASTIC and SI vulnerability assessment are relatively accurate and where large discrepancies exist between vulnerability and contamination. Furthermore, DRASTIC, SI and NO_3^- classes were compared by calculating the fraction of co-occurrence of two classes in the entire area. These plots are also shown in Fig. 12. Once again, due to the subjectivity of the plots, their purpose is merely indicative.

The DRASTIC evaluation map reveals an underestimation of the vulnerability for almost the entire area underlain by the sand aquifer in the centre and south of Campina de Faro, a large part even being extremely underestimated. The latter occurs where a 'low' and 'moderate to low' assessed vulnerability (Fig. 9) is coupled to extremely high nitrate contamination levels (Fig. 11). One could argue that DRASTIC merely assesses intrinsic vulnerability and does not account for pollution risk, defined by Foster (1987) as the interaction between aquifer vulnerability and pollutant loading. This statement is valid and partially explains why the area having an (extremely) underestimated vulnerability is much smaller in the SI map, where a parameter for land use has been included and a high pollution risk has been attributed to horticulture (LU=90) and citriculture (LU=70). However, it does not explain why underestimations continue to exist in the SI map and is even in contradiction with the overestimation that occurs in a fairly large part of the DRASTIC map of Campina da Luz. Here contamination levels are 'moderate to low' and 'low', in spite of a 'high' and 'very high' assessed vulnerability. The plot of DRASTIC versus NO_3^- clearly illustrates the low degree of correspondence between assessed vulnerability and contamination. The overall picture is better for SI, with a much larger area of correctly assessed vulnerability in Campina de Faro. However, overestimation seems to occur more frequently than with DRASTIC, with larger areas in both Campina de Faro and Campina da Luz.

The problem that lies behind the large discrepancies is that some of the hydrogeological parameters incorporated in DRASTIC (A, I, C) and SI (A) exert their influence on the contamination potential inversely to what is expected and defined by these methods. To explain this, a closer look should be given to the behaviour of nitrate. The two principal anthropogenic sources of nitrate in the study areas are chemical fertilisers and domestic wastewater leakage from septic tanks. Stigter and Carvalho Dill (2001b) demonstrated that the former 'diffuse' source has a much higher contribution to nitrate pollution than the latter 'point' sources, which can have a local importance. Fertilisers are frequently applied to the crops in excess and nitrogen in the form of NO_3^- (either directly or after nitrification of NH_4^+) can easily be flushed from the soil zone, due to its high mobility. When groundwater is extracted locally for irrigation, this induces a groundwater cycle described as follows: extraction → irrigation → return flow → extraction. When agricultural practices include irrigation, the extra recharge supplied by irrigation return flow increases the risk of leaching. Besides flushing the elements from the soil, the irrigation return flow is also highly concentrated by evapotranspiration. This process, referred to by Stigter and Carvalho Dill (2001a) and Stigter et al. (2002a) as the "groundwater recycling process", causes a gradual increase of the salinity in the upper aquifer, which is also recognised by other authors (e.g. Zaporozec 2002).

The Cl^- ion, hydrochemically considered conservative, can be used as an indicator of the groundwater recycling process, since its mass balance reflects dilution, concentration and mixing processes. Figure 13 is a plot of Cl^- versus NO_3^- concentrations in groundwater of the upper aquifers. A few samples that contain an additional Cl^- source (sea-water mixing, dissolution of evaporites) have been excluded from the plot, so as to enhance the NO_3^-/Cl^- relationship. The plot clearly illustrates that the Cl^- concentration increase induced by the groundwater recycling process is accompanied by an increase in NO_3^- concentrations. This general trend, indicated by the arrows, confirms the thesis supported by many authors (e.g. Aller et al. 1987; Appelo and Postma 1994; Canter 1997) that NO_3^- is an extremely stable ion in aerobic conditions and just as conservative as Cl^-. In the soil zone, the fate of nitrate depends on a number of factors, such as fertiliser type, fertilisation technique and rate, crop uptake and biogeochemical transformations of nitrogen. These factors, together with the possible existence of additional sources of nitrate and chloride from domestic wastewater, explain the scatter around the linear relationship between the two ions. Another phenomenon that occurs in the centre of Campina de Faro is groundwater refreshening, related to a local increase in groundwater recharge (due to the shutting down of municipal extraction wells) and the drilling of deeper wells (Stigter et al. 1998). This caused the lowering of salinity levels, but due to the continued excessive application of mineral fertilisers the tendency is not shown to the same extent by NO_3^- (as revealed by the dashed arrows in Fig. 13).

When comparing the overall trend in Campina de Faro to that of Campina da Luz, two important observations should be made. First, the slope of the NO_3^-/Cl^- relationship in Campina da Luz is less steep, which indicates a lower degree of nitrate leaching. It is difficult to point out the exact cause, since it depends on a number of factors, such as amount and method of fertiliser application, N uptake by the crop N transformations in the soil. It is quite plausible that higher amounts of N fertiliser are applied in Campina de Faro, considering the large area with horticulture, generally involving two crop cycles per


DRASTIC versus NO_3^-
SI versus NO_3^-
LEGEND
Extremely overestimated
Overestimated
Correctly estimated
Underestimated
Extremely underestimated
No information available
Road
Highway (IP1)
Railroad
Water course
0
1000
2000 m
N
FARO
Atlantic
Ocean
Luz de Tavira
Ilha de Tavira
DRASTIC
SI
NO_3^-
DRASTIC
2.9
8.4
1.8
3.5
13
5.3
2.3
2.1
4.6
7.0
6.5
3.4
6.7
6.6
1.9
5.1
4.8
4.5
1.8
3.6
4.5
19
7.5
2.4
3.8
3.0
5.3
8.3
4.0
3.0
2.1
6.1
7.2
1.8
2.0
1.8
2.6
5.7
13
17
8.1
5.4
9.5
6.2
3.4
6.3
5.5
5.7
3.8
5.7 % of total area of co-occurrence (Σ = 90%)
y = x
1
2
3
4
5
6
7
8

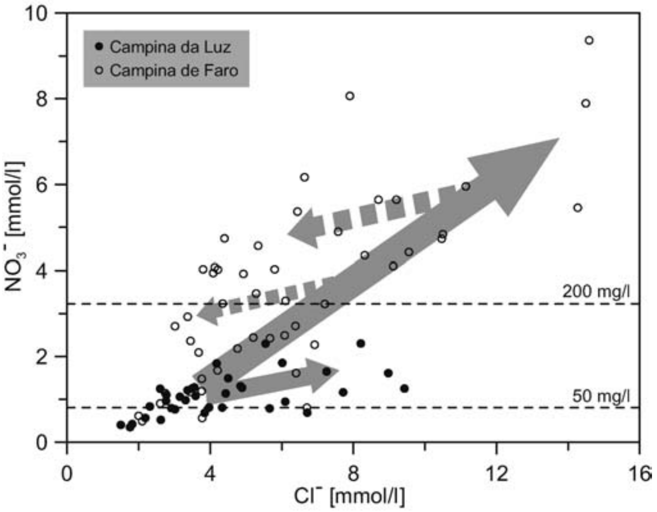


Fig .13 NO_3^- versus Cl^- concentrations of groundwater samples in the upper aquifers; *large arrow* indicates general trend of NO_3^- and Cl^- in Campina de Faro and *dashed arrows* indicate a local phenomenon (groundwater refreshening); *lowest arrow* refers to Campina da Luz with a lower NO_3^- input

year. A higher contribution of N from domestic wastewaters, due to the higher population density in Campina de Faro, can also be of some importance.

Second, the increase in NO_3^- and Cl^- concentrations is far less strong than in Campina de Faro, clearly illustrating a lower efficiency of the groundwater recycling process. In fact, this process is most efficient when groundwater residence times are high and aquifer recharge rates are low, as these conditions prevent the groundwater from leaving the system rapidly and thus promote its recycling. In the sand aquifer of Campina de Faro the relatively low hydraulic conductivity (Fig. 6) combined with a low hydraulic gradient (Fig. 2) indeed results in a high residence time. The layer of Holocene silts and clays that cover the aquifer further prevents a rapid recharge. Consequently, accumulation of NO_3^- and Cl^- is favoured, whereas at the same time attenuation of these conservative contaminants is negligible. In here lies the problem of the application of DRASTIC and SI, as these methods consider the attenuation capacity to be the most important factor when assessing vulnerability. The conditions in the upper sand aquifer of Campina de Faro supposedly promote attenuation, therefore resulting in a low assessed vulnerability. This is most likely the main cause of the underestimation by DRASTIC.

The complete opposite scenario is found in the karstified limestone aquifers of Campina da Luz. Here, recharge and discharge rates are high, travel times are low and groundwater recycling is strongly limited. The lower degree of contamination is therefore a result of dilution, which is not considered by DRASTIC or SI. Instead, these methods assume that the attenuation capacity is very low in the referred conditions and so the vulnerability to contamination is high, leading to an overestimation in these areas.

Fig. 12 **a** DRASTIC (*left*) and SI (*right*) evaluation maps of Campina de Faro (*top*) and Campina da Luz (*middle*); **b** (*bottom*): comparison of DRASTIC, SI and NO_3^- classes, labels indicating the fraction of total area (in %) of co-occurrence (very small fractions, together accounting for 10% of the area, were excluded)

By leaving out the impact of the vadose zone, SI reduces the error committed by DRASTIC and by incorporating land use, it adds valuable information. Notwithstanding these improvements, the conflicting role of parameter A (aquifer media) persists, which is also revealed by the relatively good correspondence between DRASTIC and SI classes in Fig. 12b. SI, though, tends to overestimate vulnerability, which is preferable to its underestimation, in the sense that it involves the safe side of uncertainty. In other words, if vulnerability assessment were to be used by planners or decision-makers, negative consequences of uncertainty associated to underestimation would be avoided.

Aller et al. (1987) recognise that when dilution has an important control on contamination levels, this can lead to erroneous results, as it is not accounted for by DRASTIC. Dilution has been found to play an important role in determining the degree of contamination in other parts of the world as well (e.g. Bekesi and McConchie 2002). Vulnerability assessment should not include factors such as water table depth and vadose zone material that merely determine the time it takes for a contaminant to reach the aquifer. A rapid arrival of the contaminant at the aquifer should not automatically be synonymous to a high vulnerability, such as implied by DRASTIC and SI. Rather, factors such as cleansing capacity of the soil and restoration capability of the aquifer should be given more emphasis, as was already suggested by Andersen and Gosk (1987). According to Johansson and Hirata (2002) evaluating vulnerability is not even that important in a long-term sustainability context, when dealing with very mobile and persistent contaminants.

If vulnerability assessment is to be an efficient tool in groundwater management policies, it should focus on specific contaminant groups or polluting activities. Therefore, it should be combined with the classification of contamination sources, as proposed by Zaporozec (2002). Groundwater value assessment will provide a valuable contribution in evaluating the consequences of contamination events (Zaporozec 2002). Simultaneous estimates of the contaminant load on groundwater should be made (in the case of nitrate for instance by analysing N balances in the soil). Other methodologies for predicting future evolutions of contaminant concentrations, based on deterministic or probabilistic approaches, should also be applied whenever possible. The goal should always be to make the vulnerability assessment as rigorous as possible, thereby reducing the chance of erroneous decisions (for instance on which areas require more protection against contaminating activities).

Conclusions

Nitrate contamination and salinisation levels in the study areas are mainly controlled by two factors: (1) the volume of nitrogen input at the surface, which depends on land use, and (2) the efficiency of the groundwater recycling process. The conservative behaviour of these contaminants does not permit a correct vulnerability assessment by intrinsic methods such as DRASTIC, which ascribe a great significance to the attenuation capacity of the involved hydrogeological parameters. It is clearly proved in the case studies that dilution rather that attenuation is the key factor in lowering the contamination levels.

The application of the Susceptibility Index for diffuse agricultural pollution is a good example of specific vulnerability assessment. The results obtained by this method clearly benefit from the incorporation of land use in the index calculations. However, the method still evaluates the behaviour of the aquifer media in the same way as DRASTIC and also includes depth to groundwater. Leaving the soil properties out of SI does not have a large impact, as its weight in DRASTIC is already rather low. However, the influence of this parameter on the degree of contamination requires further study. Finally, high recharge and flat topography contribute to high vulnerability as well as high nitrate and salinisation levels, meaning that the behaviour of these parameters is consistent.

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