Assessment of sustainability of groundwater in urban areas (Porto, NW Portugal): a GIS mapping approach to evaluate vulnerability, infiltration and recharge

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Abstract
The urban water cycle concept demonstrates the connectivity and interdependence of urban water resources and human activities, and the need for integrated sustainable management studies and approaches. The role of climate, geology, geomorphology, land-use/cover, hydrogeochemistry, hydraulics, human activities among other features is significant in urban areas. In addition, land-use development has a stronger influence on terrestrial hydrology than climate variability. The need for provision of safe water, sanitation and drainage systems is key elements to consider for the groundwater resources in complex urban environments. In recent years, a new focus has emerged, addressing issues on integrated GIS mapping studies on urban water supply systems, particularly in historical cities. To illustrate that approach the Porto urban area (NW Portugal) was selected. This work presents a comprehensive study to demonstrate the key importance of urban groundwater studies, as well as the evaluation of the Urban Infiltration Potential Index and the potential groundwater yields that might be available for non-potable uses, such as irrigation of parks and lawns, street cleaning and firefighting. This strategy is useful for the planning and management of urban groundwater abstraction in an equitable and sustainable manner.

Keywords Urban groundwater · Hydrogeomorphology · Vulnerability · IPI-Urban · Sustainability

Introduction

The urban water cycle provides a conceptual and unifying basis for a reliable assessment of groundwater systems and conducting the basis of the sustainable water resource studies. Impact of climate variability addresses one of the most important drivers for development of urban water cycle systems (Afonso et al. 2016; Chaminé et al. 2016; Rathnayaka et al. 2016). The city blueprint approach comprises a sustainable use of urban water cycle services which include several dimensions as social, environmental, economic, assets and governance (e.g. van Leeuwen et al. 2012; Foster and MacDonald 2014; Howard 2015; Koop and van Leeuwen 2015a, b; Marques et al. 2015; Sægrov et al. 2016). In recent years, the groundwater blueprint is seen as a finite, vulnerable, but a resilient natural resource to be protected in an environmentally sustainable way (e.g. Foster and Ait-Kadi 2012; Rockström et al. 2014; Chaminé 2015; Ilmola 2016). In addition, hydroclimatology, hydrogeomorphology, hydrogeology and hydrogeochemistry, groundwater ecotoxicology and geomicrobiology, hydraulic and sanitary engineering, as well as hydrotoponymy, hydroarchaeology, economic and societal studies are essential to achieve a correct understanding of the overall framework of the urban water systems (e.g. Afonso et al. 2010, 2016; Freitas et al. 2014; Re 2015; Stigter et al. 2017; Miller et al. 2018). Finally, reliably efforts must be performed to observe humans in relationship to the sustainability water environment, particularly over time and at several scales, and the need for coordinated data collection (David 1971; Ettazarini 2007; Braden et al. 2014; Sivapalan et al. 2012).

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An urban population demands high quantities of energy and raw materials, and removal of waste, some of which turn into environmental contamination and pollution of ground and water resources. Urbanisation is a worldwide trend, with more than 54% of the world's population currently living in cities, mostly located along coast zones and major streams (Margat and van der Gun 2013; Koop and van Leeuwen 2015b; Kaushal et al. 2015). Furthermore, urban areas are expected to increase to 66% and continuing population growth and urbanisation are projected to add 2.5 billion people to the world's urban population by 2050 (UN 2014).

Integrated Water Resources Management (IWRM) framework becomes even more challenging due to the rapid urbanisation, climate variability and climate change pose increasing pressures in urban areas, especially in groundwater blueprint (e.g. Foster and Ait-Kadi 2012; Chaminé 2015; Koop and van Leeuwen 2015a, b). A keen evaluation of the vulnerability, infiltration and recharge is a comprehensive approach to a sustainable water resource management in urban areas.

Groundwater vulnerability assessment must be interrelated with and integrated into master plans to support the planning, policy and strategy of groundwater resource protection and quality conservation (e.g. Civita 2010; Foster et al. 2011; Srinivasan et al. 2013; Chaminé et al. 2015; Howard 2015). Accordingly, Martínez-Navarrete et al. (2013) state it is essential to validate—in various media, with different pressures and socioeconomic conditions—a management tool that integrates the protection of groundwater in the planning process, considering the economic assessment of different management scenarios.

Groundwater vulnerability to contamination involves two concepts (Zaporozec 2004): intrinsic (or natural) vulnerability and specific (or integrated) vulnerability. The evaluation of aquifer vulnerability is an important basis to fulfill demands of the EU Water Framework Directive (WFD) and the EU Groundwater Directive. The WFD required that all surface waters and groundwaters should reach good status by the year 2015. Assessing the vulnerability of aquifer systems in urban environments is a major challenge since the city ground is often covered by geomaterials, which have distinctive features from natural bedrock and are produced, altered or displaced by mankind. Moreover, urban groundwater quality is frequently very threatened due to numerous and inadequately controlled contamination sources, especially given the close connection between wastewater and underlying groundwater systems (e.g. Haase 2009; Foster et al. 2011; Srinivasan et al. 2013).

Recharge occurs when water flows past the groundwater level and infiltrates into the saturated zone. Urban total recharge comprises direct, indirect, artificial and localised processes, which overlap and are not mutually exclusive (e.g. Massing et al. 1990; Yang et al. 1999; Sharp et al. 2001; Lerner 2002; Garcia-Fresca and Sharp 2005; Sharp 2010; Vázquez-Suñé et al. 2010; Afonso et al. 2016; Hibbs 2016; Tubau et al. 2017).

Many features contribute to the circulation of urban groundwater, including lithology, morphotectonics, weathering degree, slope, drainage patterns, land use/cover, and climate. In addition, it is decisive the influence of the intricate system of man-made infrastructures (e.g. sewer, storm sewers, pipes, trenches, tunnels, and other buried structures) and impervious surfaces and or cover areas (Wiles and Sharp 2008; Verbeeck et al. 2011; Hibbs and Sharp 2012; Afonso et al. 2016; Attard et al. 2016).

In this work, several methods were implemented, taking advantage of a GIS-based mapping, to assess aquifer vulnerability to contamination of Porto urban area (NW Portugal), namely GODS, DRASTIC, SINTACS and SI. An exhaustive inventory of potential contamination sources occurring at the surface and shallow ground was performed to improve that assessment. A delineation of groundwater favourable potential zones was performed using the IPI-Urban and complemented with the urban recharge. This study enhances our knowledge of groundwater vulnerability, infiltration and recharge in urban centres and addresses key drivers to design aquifer protection and management strategies.

Porto urban area

The Porto urban area has been developed on granitic hill slopes of Douro riverside, nearby the Douro River mouth and the Atlantic Ocean (Fig. 1). Porto is a historical city in Europe, its past dating back to at least the sixth century and became an important settlement in the twelfth century (de Oliveira Marques 1972). Nowadays, Porto is the second biggest metropolitan area in mainland Portugal, with almost 1.3 million inhabitants (Costa-Lobo 1991). In addition, it has a relatively small area (41.3 km^2) and its current population is 237,559 inhabitants (INE 2011), which gives this area the highest population density (ca. 5750 inhabitants/km^2) of any of the surrounding cities (Afonso et al. 2016).

Porto urban area has a temperate climate, with a dry and warm summer (Köppen climate classification Csb). The average annual temperature is 15.2 °C. The area has a water deficit from June to September, particularly in July and August. The average annual rainfall is 1236.8 mm/year, reaching 187.1 mm in the rainiest month (December) and 20.4 mm in the driest month (July).

Regional hydrogeologic units in Porto urban area include (Table 1): porous media including alluvia and fluvial/marine deposits, constituted by coarse (sands and gravel) to fine (silt and clay) sediments, which are generally of limited extent and with low thicknesses (< 6 m; COBA 2003); metasedimentary rocks (e.g., micaschists,

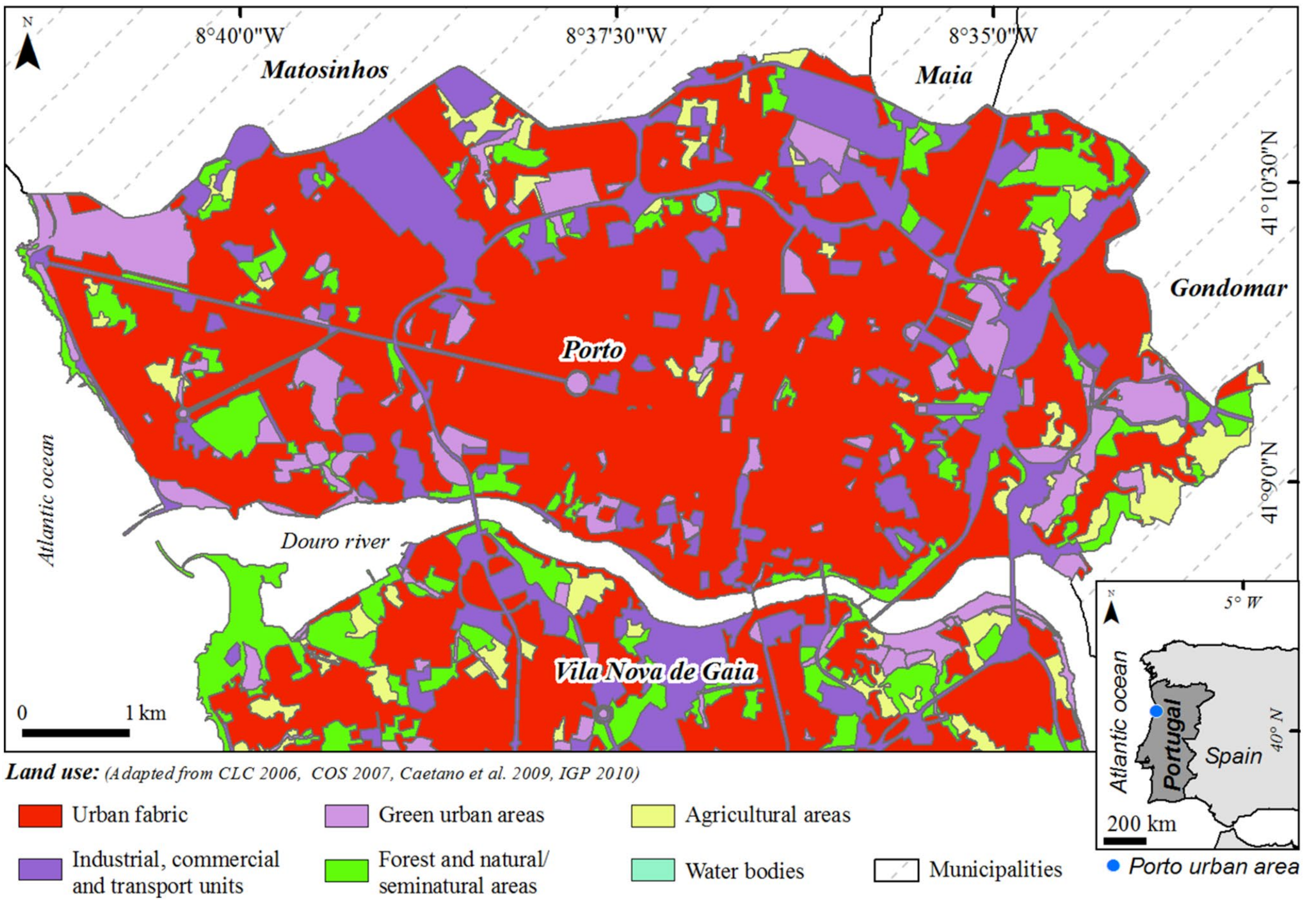


Fig. 1 Land-use categories in Porto urban area and surroundings

schists and metagraywackes) and granitic rocks (granites and gneisses) correspond to the fissured medium (Chaminé et al. 2010). Granites dominate the region, particularly the two-mica, medium- to fine-grained facies, the so-called "Porto granite" (Begonha and Sequeira Braga 2002; Almeida 2006). This granitic bedrock is, generally, weathered to different grades, from fresh rock to residual soil (saprolite mass), in short distances, resulting in arenisation and kaolinisation that may extend to depths of over 30 m (e.g., Begonha and Sequeira Braga 2002; Gaj et al. 2003).

Most part of the study area is occupied by the urban fabric (59.9%); second are industrial, commercial and transport units (16.8%); forest and natural/semi-natural areas occupy 10% of the site and are most representative in Vila Nova de Gaia city; green urban areas are also more frequent in this city, with 8.8%; agricultural areas occupy 4.4% and, finally, water bodies, except the Douro river, do not have a cartographic expression (Fig. 1).

Materials and methods

Figure 2 shows a methodological flowchart to assess urban groundwater studies in Porto area (ca. 52 km^2). This integrative methodology was applied using the GIS technology (ArcGis 9.3 platform). An interactive geo-database was created to organise and analyse the spatial data (e.g. topography, land use, geology, morphotectonics, hydrogeological features, hydroclimatology, net recharge, urban hydraulics and sanitation, hydrotoponymy, and inventory of surface and shallow groundwater potential contamination activities). The record of shallow groundwater potential contamination activities was developed including them in some categories, by origin (after Zaporozec 2004): (1) urbanisation, (2) industry, (3) agriculture, (4) water mismanagement, and (5) miscellaneous. All these activities were identified and georeferenced using a high-accuracy GPS device (Trimble® GeoExplorer) and a field inventory datasheet was created.

Hydrogeological units and related features in the Porto urban area (updated from Afonso et al. 2007)

Regional hydrogeological groups (updated from Afonso et al. 2007)	Hydrogeological units (UH)	Hydrogeological features										
		Connectivity to the drainage stream system			Dominant flow type		Weathering				More suitable water abstraction structures	
		With	Without	Possible	Porous media	Fissured media	Low thickness	High thickness	Clayey	Sandy	Dug-wells, galleries and springs	Boreholes
Sedimentary cover	Sand and gravel—UH 1	X			X		n.a				X	
	Alluvia (including waste disposal areas, wd)—UH 2	X			X		n.a				X	
	Arenite and conglomerate deposits—UH 3	X			X		X		X	X	X	
Metase dimentary rocks	Micaschist, schist and greywacke—UH 4			X		X		X	X			X
Granitic rocks and gneisses	Granite, medium to coarse grained, with feldspar megacrystals—UH 5			X		X	X	X		X	X	X
	Granite, medium to fine grained, with saprolite (sp) masses—UH 6			X		X		X	X	X	X	
	Gneiss and micaschist—UH 7			X		X	X	X		X	X	X

n.a not applicable

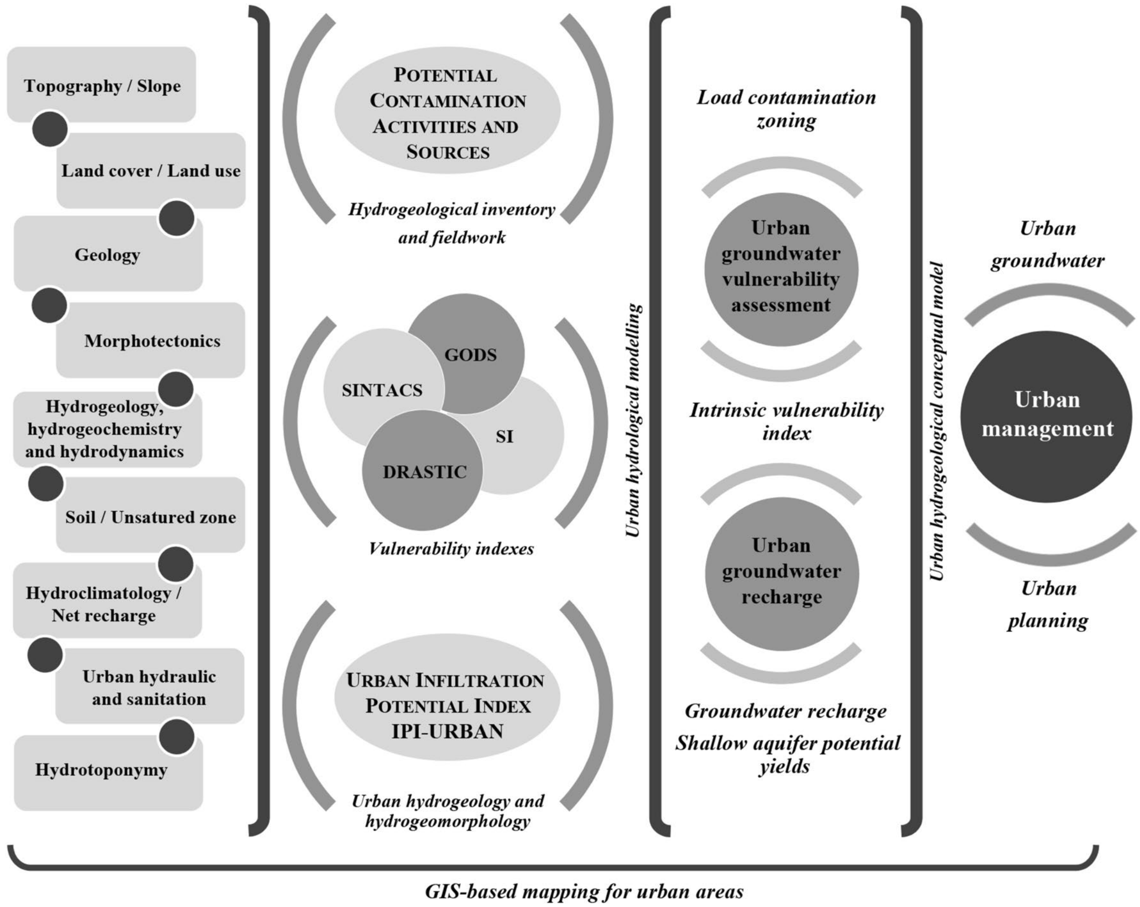


Fig. 2 Conceptual methodological flowchart for the study in Porto urban area (NW Portugal)

Several indexes were used for the evaluation of vulnerability, such as DRASTIC (Aller et al. 1987), GODS (Foster et al. 2002), SINTACS (Civita 1994, 2010) and SI (Francés et al. 2001; Ribeiro et al. 2017). For SINTACS, the weights of severe and fissured strings were used (Civita 2010): the severe string was applied in areas where sedimentary cover/saprolite is related to the land-use (LU) categories "urban fabric" and "industrial, commercial and transport units"; the fissured string was a correspondence of the metasedimentary, granitic and gneissic rocks with the LU classes "green urban areas", "forest and natural/semi-natural areas" and "agricultural areas". Concerning SI, the LU parameter was derived from the land-cover and the land-use maps (EEA 2007, Caetano et al. 2009; COS2007; IGP 2010).

Hydrogeological background was based on the vulnerability assessment. The international colour code was used for DRASTIC index ranges. Finally, an integrated evaluation between all the methods was performed permitting to achieve an urban groundwater vulnerability assessment. Table 2 summarises the methods used to evaluate the intrinsic vulnerability.

The explaining factors used in the indexes were based, revised and updated from the key bibliography (e.g., Jaiswal et al. 2003; Yeh et al. 2009; Jha 2011; Teixeira et al. 2013, 2015). The relative weight and score for each factor was calculated using the analytical hierarchy process (AHP), a theory and procedure for comparative measurement. The goal of the AHP is to use pairwise evaluations between alternatives as inputs, comparing all the criteria to one another, to evaluate a rating or weighting of each criteria that describes the importance of each of these criteria in contributing to the overall objective (e.g., Saaty 2008, 2012; Kim et al. 2009; Brunelli 2015; Mu and Pereyra-Rojas 2017). The inner scores were assessed from the fieldwork data. The input maps have been used to calculate the IPI-Urban based on the conditions and features of: (1) geology and morphotectonics; (2) climate and hydrology; (3) urban hydrogeology and hydrogeomorphology; (4) urban hydraulics and sanitation. The IPI-Urban is a weighted sum of eight factors: hydrogeology, tectonic lineament density, land use, drainage density, slope, sewer network density, stormwater network density and water supply network. The last three factors are directly related to urban hydraulic and sanitation. All these factors

Table 2 Methodological overview of the methods applied in the assessment of the intrinsic vulnerability of urban groundwater

Methods (key studies)	DRASTIC Aller et al. (1987)	GODS Foster (1987), Foster et al. (2002)	SINTACS Civita (1994, 2010), Civita and De Maio 2000)	SI Francés et al. (2001), Ribeiro et al. (2017)
Brief description	Point count system model for the evaluation of intrinsic vulnerability. The method considers some parameters and the vulnerability is expressed by 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*, where index *r* refers to the range and *w* refers to the assigned weight. The vulnerability classes are: < 80, 80–100, 100–120, 120–140, 140–160, 160–180, 180–200, and > 200	Rating system model for the evaluation of intrinsic vulnerability. Adaptation of GOD method, where four parameters are considered. The integrated aquifer vulnerability index is the final product of component indexes for these parameters. The vulnerability classes are: 0.0–0.1 (negligible), 0.1–0.3 (low), 0.3–0.5 (moderate), 0.5–0.7 (high) and 0.7–1.0 (extreme)	Point count system model for the evaluation of intrinsic vulnerability. Derived from DRASTIC, this method uses the same seven parameters as DRASTIC, but the rating and weighting procedure is more flexible. This method provides six strings of multiplier weights that can be used in parallel: normal, severe, seepage, karst, fissured and nitrates. The vulnerability index is: S*r*S*w* + I*r*I*w* + N*r*N*w* + T*r*T*w* + A*r*A*w* + C*r*C*w* + S*r*S*w*, with *r* and *w* meaning the same as DRASTIC. The vulnerability classes are: 26–80 (very low), 80–105 (low), 105–140 (moderate), 140–186 (high), 186–210 (very high), and 210–260 (extremely high)	Point count system model for the evaluation of intrinsic vulnerability. Derived from DRASTIC, this method uses the same seven parameters as DRASTIC, which has incorporated the "land-use" parameter, having been developed to evaluate the aquifer vulnerability to diffuse agricultural pollution. The vulnerability index is: 0.186D + 0.212R + 0.259A + 0.121T + 0.222Lu. The vulnerability classes are: < 30 (extremely low), 30–40 (very low), 40–50 (low), 50–60 (moderate to low), 60–70 (moderate to high), 70–80 (high), and 80–90 (very high)
Parameters				
D	×	×	×	×
R	×		×	×
A	×	×	×	×
S	×	×	×	×
T	×		×	×
U	×	×	×	×
LU				×

D depth to groundwater, *R* recharge/infiltration, *A* aquifer characteristics (lithology, weathering grade, hydraulic conductivity, groundwater confinement, fracturing degree), *S* soil media, *T* topography/slope, *U* unsaturated zone characteristics (lithology, hydraulic conductivity), *LU* land use were spatially represented and analysed in a GIS-based mapping approach. The result of this GIS analysis is a map (a grid with a pixel of 5×5 m^2), where it is possible to observe the spatial variation of the IPI-Urban. The IPI-Urban represents the combination of all factors, ranging from 0 to 100. The higher values represent better conditions for water infiltration, according to all factors.

For the IPI-Urban analysis, two scenarios were developed related to the seasons, namely summer and winter scenarios. The weight of the factors set out above was modified according to these scenarios. In the summer scenario, the density map of stormwater network was not considered, as the study area is hot and dry in summer. For the summer scenario, the factors and their weights are: hydrogeology (25.8%); land use (22.1%); slope (15.3%); tectonic lineament density (14.6%); water supply network (10.2%); sewer network density (6.3%) and drainage density (5.7%). In the winter scenario, the weights are: hydrogeology (25.1%); tectonic lineament density (16.2%); land use (15.8%); water supply network (13.2%); slope (13.2%); sewer network density (5.9%); stormwater network density (5.8%) and drainage density (4.7%). An urban hydrogeomorphological map was shaped, overlapping the geomorphological map and the urban potential infiltration index map.

To calculate the urban recharge, an analysis of the average rainfall data in the area was performed, showing that the months of June, July, August and September are predominantly dry. The yearly average for dry months was used to calculate the recharge in the summer scenario. The remaining months (wet period) were used for the winter scenario. An 8% value was used as initial recharge rate, according to regional hydrogeologic key studies (Afonso et al. 2007; Afonso 2011). The yearly rainfall averages of 165.1 mm and 1071.7 mm were thus considered for the summer and winter scenarios, respectively. In each scenario, the urban recharge map (mm/year) was divided by the rainfall value, to obtain the urban recharge rate (%). The urban recharge map (mm/year) was then converted to the L/s/km^2 unit, resulting in the shallow aquifer potential yield map.

Results and discussion

The degradation of groundwater quality can be originated from several activities of contamination and or pollution. These activities were typified according to the Zaporozec's works (e.g. Vrba and Zaporozec 1994; Zaporozec 2004), and they are mapped as points, lines and areas. An inventory of surface and shallow groundwater potential contamination activities was realised, and it is presented in Fig. 3. For the development of this inventory, several fieldwork campaigns were performed. Figure 3 shows an example of a detailed mapping of the *Vilar Catchment* sector to facilitate the visualisation of the inventory.

The inventory was organised into several categories and corresponds to a total of 867 potential contamination sources, such as: (1) urbanisation; (2) industry; (3) water mismanagement; (4) miscellaneous; (5) groundwater (Table 3). According to the urban characteristics of the study area, the most representative category is urbanisation (86%), followed by groundwater (9.7%). The remaining 4% are divided into three classes: miscellaneous (2.4%), industry (0.9%) and water mismanagement (0.9%). Within the urbanisation class, it has been found that there are more automobile repair shops (37.7%) and school/university buildings (37.1%). These two classes correspond to 74.8% of the potential contamination activities related to the urbanisation category. The remaining 25.2% are divided for the rest of the classes, namely petrol stations (6%), healthcare units (5.1%), public washing places (4%), veterinary clinics or hospitals (2.8%), hospitals (2.8%), garages (2.5%) and public gardens (1.9%). A considerable number of the inventoried sources are of point source character and their dominant potential contamination load, according to the Zaporozec's (2004) proposal, is moderate.

The study of the vulnerability of groundwater to contamination in the Porto urban area was based on the cross-check of several vulnerability indexes. Figure 4 presents the GODS and DRASTIC vulnerability maps (cf. Table 2). An association between the GODS Index and the hydrogeological units (cf. Table 1) can be performed. The GODS vulnerability map (Fig. 4a) shows that a significant part of the area (ca. 41%) has a low-moderate vulnerability. The hydrogeological unit that represents this class of vulnerability is UH6 (granite medium to fine grained). The classes moderate–high and high vulnerability represent 24.9% of the study area, corresponding to the hydrogeological units UH3 (arenite and conglomerate deposits) and UH2 (alluvia), respectively. The metasedimentary rocks (UH4) and the saprolite masses (UH6) are characterised by a negligible vulnerability, corresponding to 18.4% of the area. The low vulnerability areas (12.4%) are related to granitic rocks (UH5). Gneisses (UH7) have negligiblely low vulnerability (ca. 1.8%). The extreme vulnerability (1.5%) is linked to the sand and gravel areas (UH1). Similar conclusions were reached by Afonso et al. (2016) in an area in Porto city. Figure 4b presents the DRASTIC index. Although they are considered more parameters in this index, a comparison with the hydrogeological units can be performed. Half of the area (56.1%) has a moderate vulnerability, corresponding mainly to the UH5 and UH6 hydrogeological units (cf. Table 1). Moreover, the areas with a high–very high vulnerability (28.2%) comprise the UH2 and UH3 hydrogeological units. Furthermore, the low vulnerability has a significant cartographic representation (9%), characterised by UH6 hydrogeological unit. Low–moderate

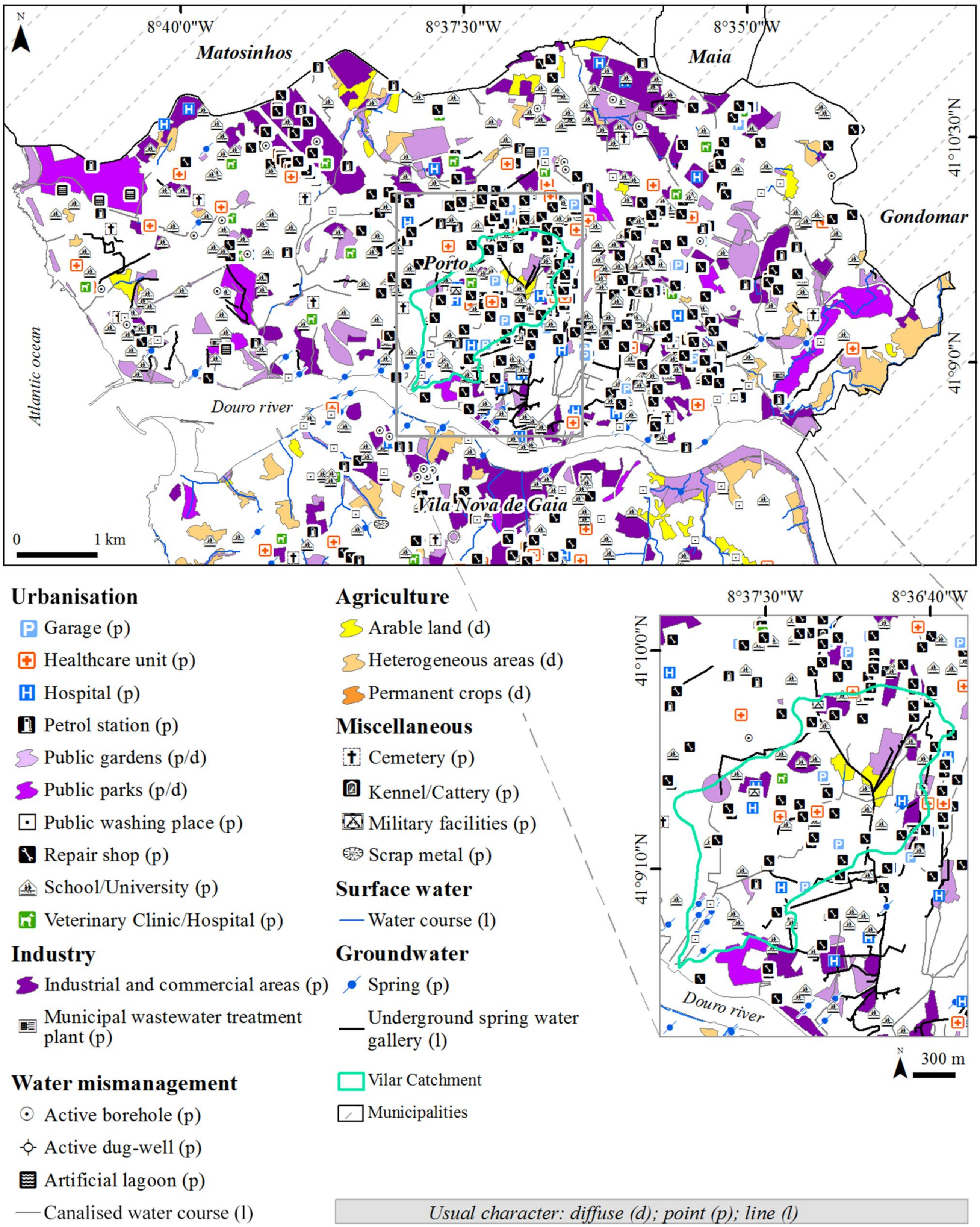


Fig. 3 Groundwater potential contamination activities in Porto urban area (NW Portugal)

Table 3 Potential contaminations sources: statistical overview

Categories	Potential contamination activities	Number of activities	%	Total	%
Urbanisation	Veterinary clinic/hospital	21	2.4	746	86.0
	School/university	277	31.9		
	Repair shop	281	32.4		
	Garage	19	2.2		
	Hospital	21	2.4		
	Public gardens	14	1.6		
	Public washing place	30	3.5		
	Petrol station	45	5.2		
	Healthcare unit	38	4.4		
Industry	Industries	5	0.6	8	0.9
	Municipal wastewater treatment plant	3	0.3		
Miscellaneous	Cemetery	13	1.5	21	2.4
	Kennel/cattery	1	0.1		
	Military facilities	4	0.5		
	Scrap metal	3	0.3		
Water mismanagement	Active dug-well/borehole	3	0.3	8	0.9
	Artificial lagoon	5	0.6		
Groundwater	Spring	84	9.7	84	9.7
Total		867	100	867	100

vulnerability corresponds to 5% of the total area that seems to be related with the clayey soil masses (UH4 and UH7). The most vulnerable areas are also associated with the sand and gravel deposits (UH1), which are quite porous and permeable. Again, analogous conclusions were attained by Afonso et al. (2016).

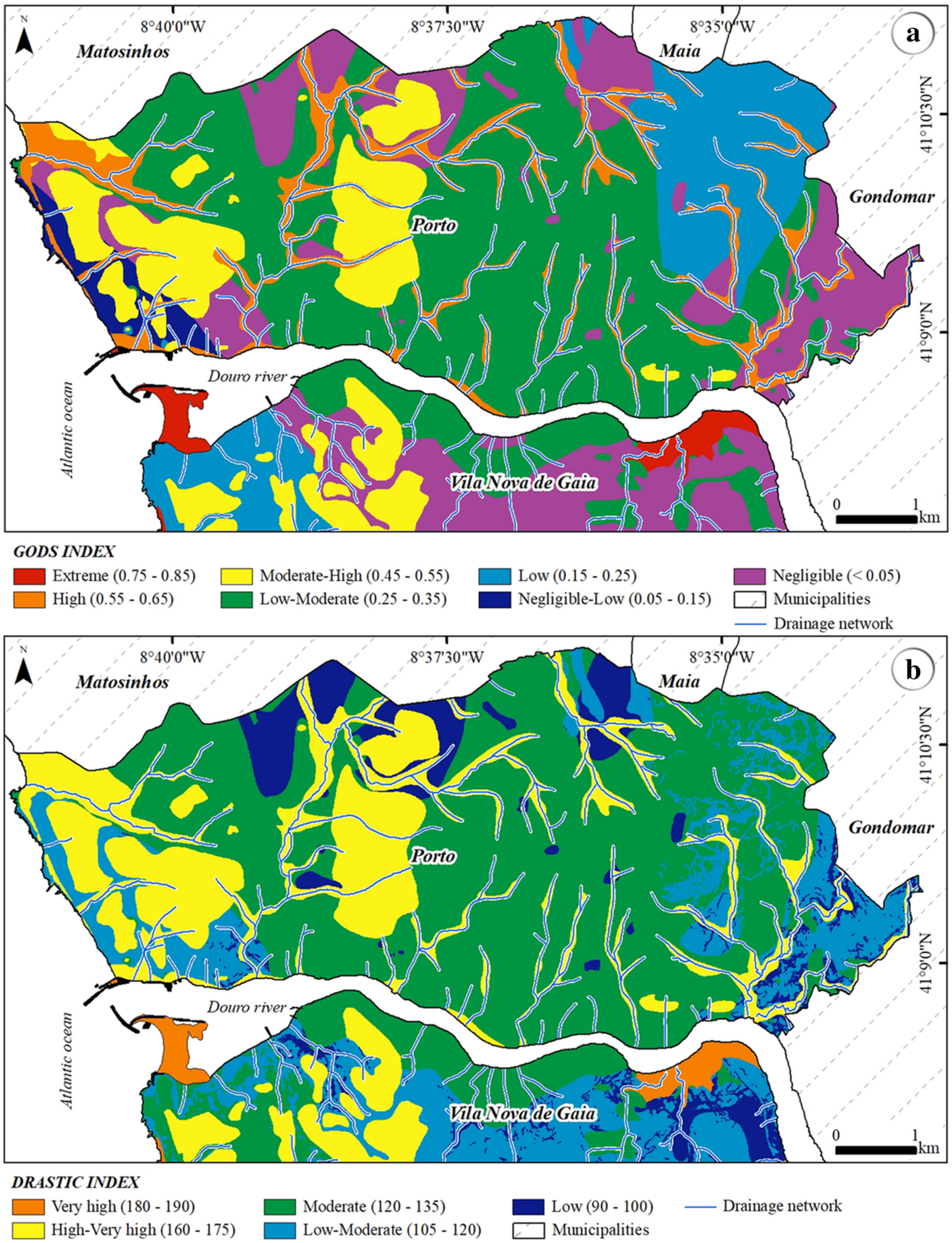
Figure 5 shows the SINTACS and SI indexes (cf. Table 2). The analysis of the SINTACS index (Fig. 5a) allows to conclude that a significant part of the area (41.3%) presents a high vulnerability to contamination. The moderate vulnerability class corresponds to 29.7% of the study area and the very high–extremely high class is related to 25.3% of the area. Therefore, according to this index, the study area is mostly characterised (71%) by a high to moderate vulnerability. These results are coherent with those obtained by Afonso et al. (2016).

Regarding the SI index (Fig. 5b), the vulnerability is predominantly moderate–high to high (71.8%), having these classes similar proportions. The low–moderate class represents 202.2%. On the other hand, the extreme classes, very low–low and very high, are much less representative in the area (ca. 8%).

Figure 6 shows the IPI-Urban for the summer scenario (a) and the winter scenario (b). The weight of the factors was adapted according the scenarios. The geomorphological framework displays an alternation between flattened areas and valleys of secondary water courses. The altitude of the flattened areas increases from west to east and from south to north. The highest altitudes are in the northeastern part of the urban area (ranging between 130 and 160 m). The lowest altitudes (< 25 m) occur on the west area.

Regarding the IPI-Urban Index, it is interesting to note that in both scenarios low to moderate areas are predominant, corresponding to 58% in the summer scenario and 47% in the winter scenario. Regarding summer scenario, 29.9% of the area has a very low to low IPI-Urban. However, the high class of IPI-Urban represents 11.9% of the study area. This can be explained by the importance that hydrogeology and land use acquire in this scenario (47.9%). So, the high IPI-Urban occurs where green urban areas (cf. Fig. 1) coexist with the hydrogeological units UH1, UH2 and UH3 (cf. Table 1). The very high IPI-Urban has a low representation (0.2%) and usually occurs at the valleys of the secondary water courses. For the winter scenario, most of the area (47%) has a low to moderate IPI-Urban. Very low to low IPI-Urban represents 40% of the area and the high class constitutes 12.6%. The spatial distribution of the index follows the summer scenario. However, the loss of importance of the land use factor further decreases the very high class (0.4%). The winter scenario highlights the importance of the tectonic lineament density, which is probably responsible for the high IPI-Urban index.

The urban groundwater recharge rate was estimated using a proportion of precipitation for each scenario (Fig. 7). The minimum and maximum recharge rates are 1.4% and 7.1%, and 1.5% and 6.8% for the summer and winter scenarios, respectively. The median recharge rate for the urban area



GODS Index Classes	%
Extreme (0.75 - 0.85)	1.5
High (0.55 - 0.65)	11.9
Moderate - High (0.45 - 0.55)	13.0
Low - Moderate (0.25 - 0.35)	41.0
Low (0.15 - 0.25)	12.4
Negligible - Low (0.05 - 0.15)	1.8
Negligible (< 0.05)	18.4

DRASTIC Index Classes	%
Very high (180 - 190)	1.7
High - Very high (160 - 175)	28.2
Moderate (120 - 135)	56.1
Low - Moderate (105 - 120)	5.0
Low (90 - 100)	9.0

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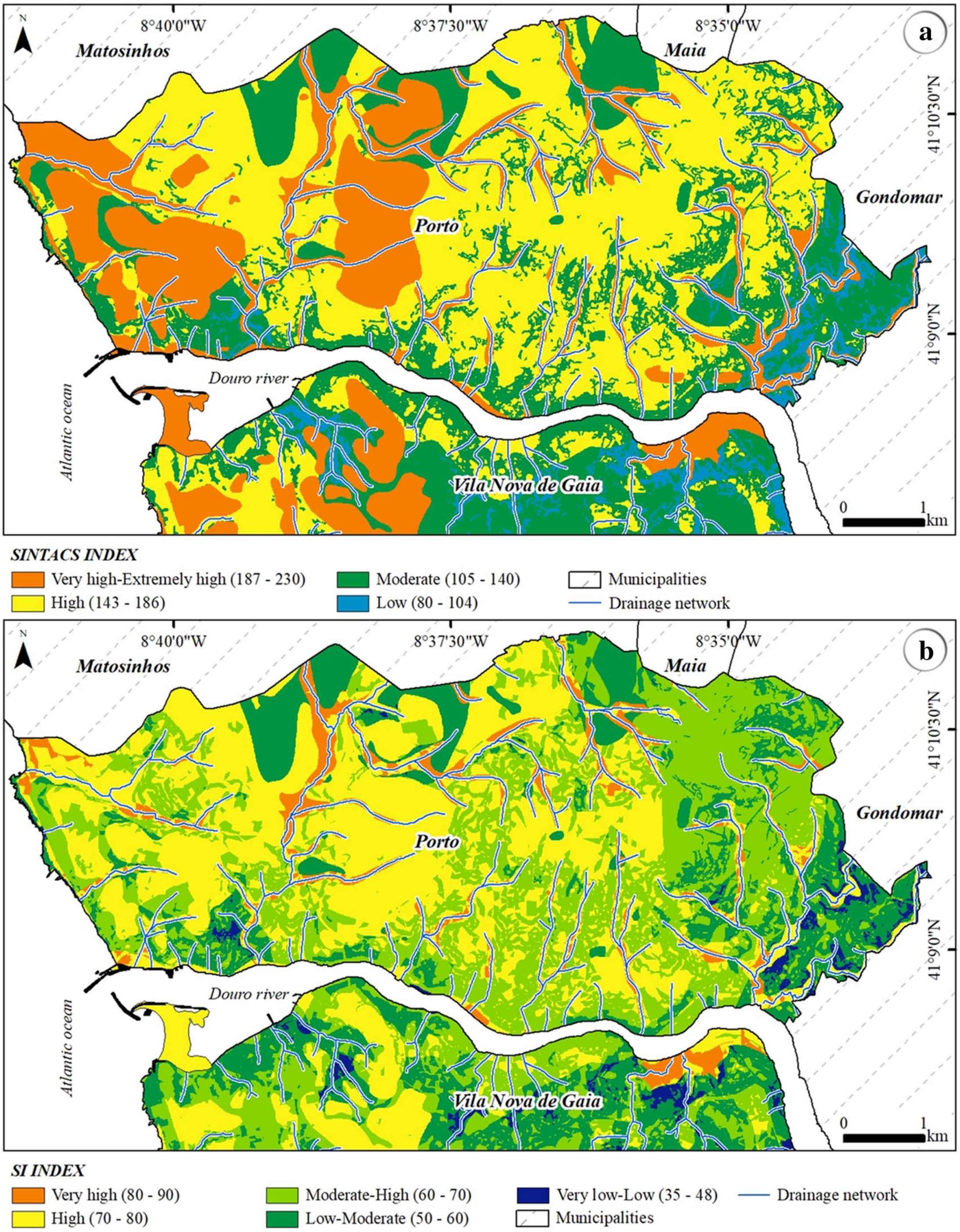
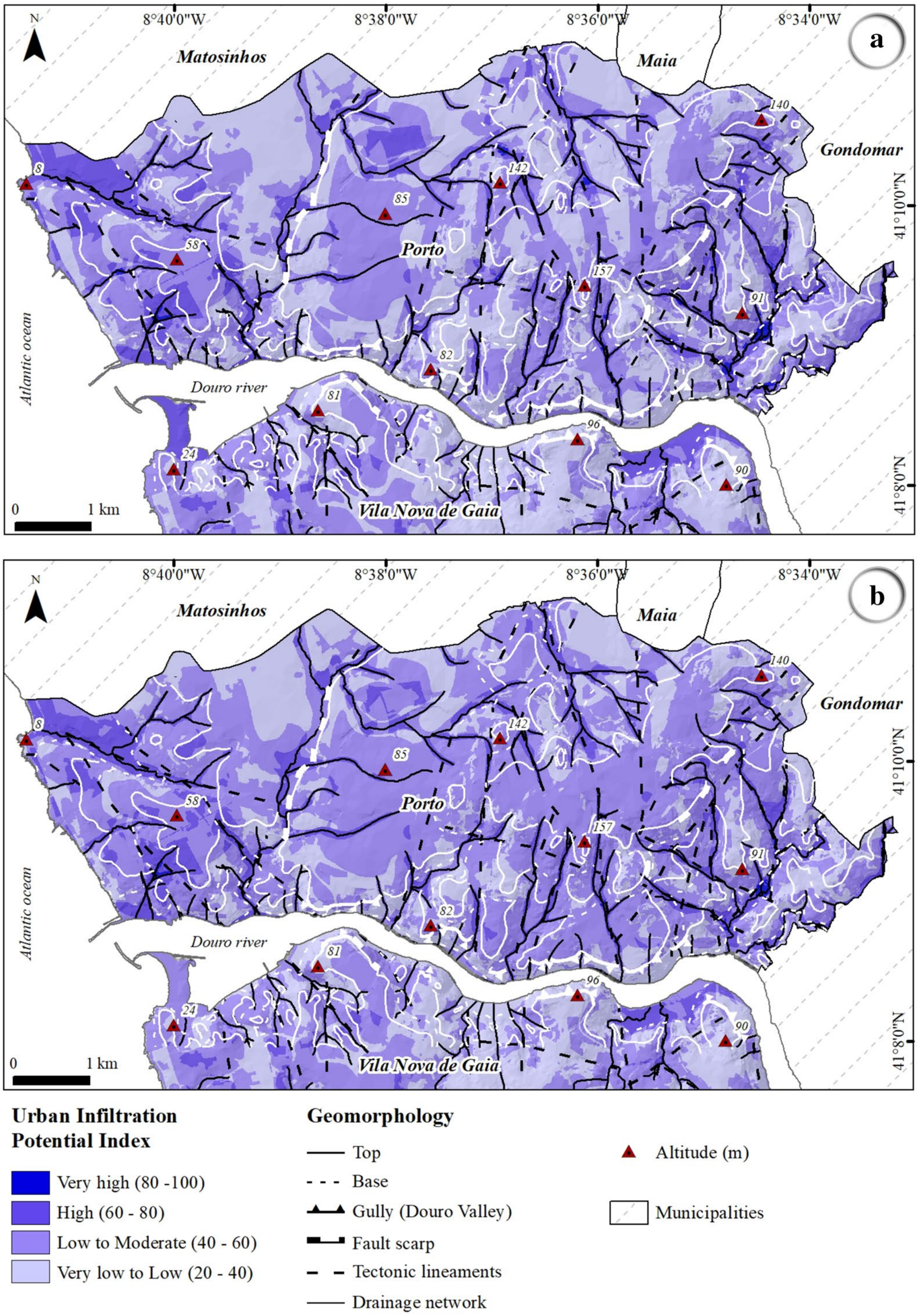


SINTACS Index Classes	%
Very high - Extremely high (187 - 230)	25.3
High (143 - 186)	41.3
Moderate (105 - 140)	29.7
Low (80 - 104)	3.7

SI Index Classes	%
Very high (80 - 90)	6.1
High (70 - 80)	36.3
Moderate - High (60 - 70)	35.5
Low - Moderate (50 - 60)	20.2
Very low - Low (35 - 48)	1.9

c

Fig. 5 Porto urban area and surroundings: SINTACS **a** SI, **b** vulnerability maps and **c** statistical overview for the two scenarios



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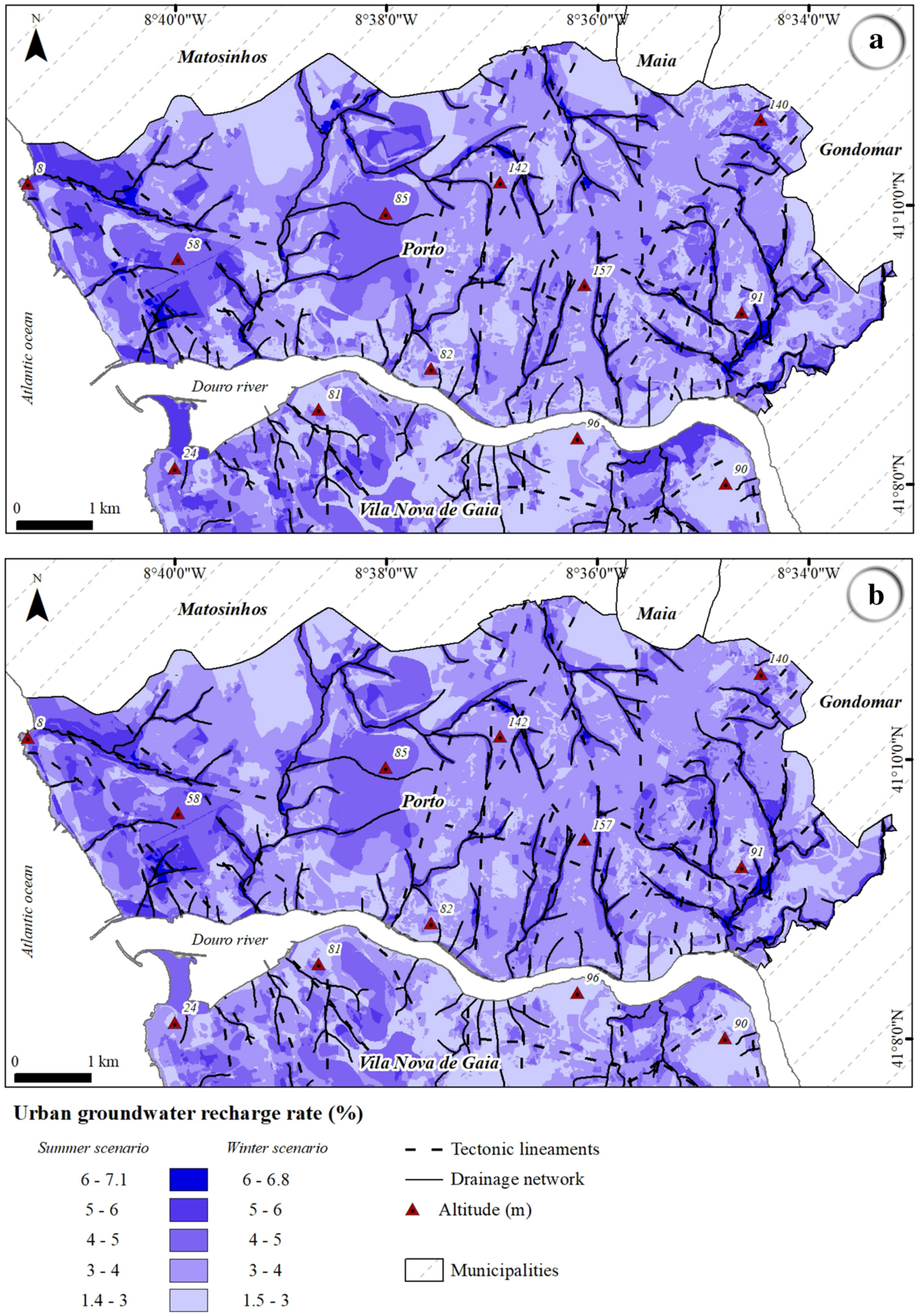
Urban Infiltration Potential Index Classes (IPI-URBAN)	Summer scenario	Winter scenario
	%	%
Very high (80 - 100)	0.2	0.4
High (60 - 80)	11.9	12.6
Low - Moderate (40 - 60)	58.0	47.0
Very low to Low (20 - 40)	29.9	40.0

Fig. 6 Urban Infiltration Potential Index (IPI-URBAN) of Porto urban area and surroundings: **a** summer scenario; **b** winter scenario and **c** statistical overview for the two scenarios

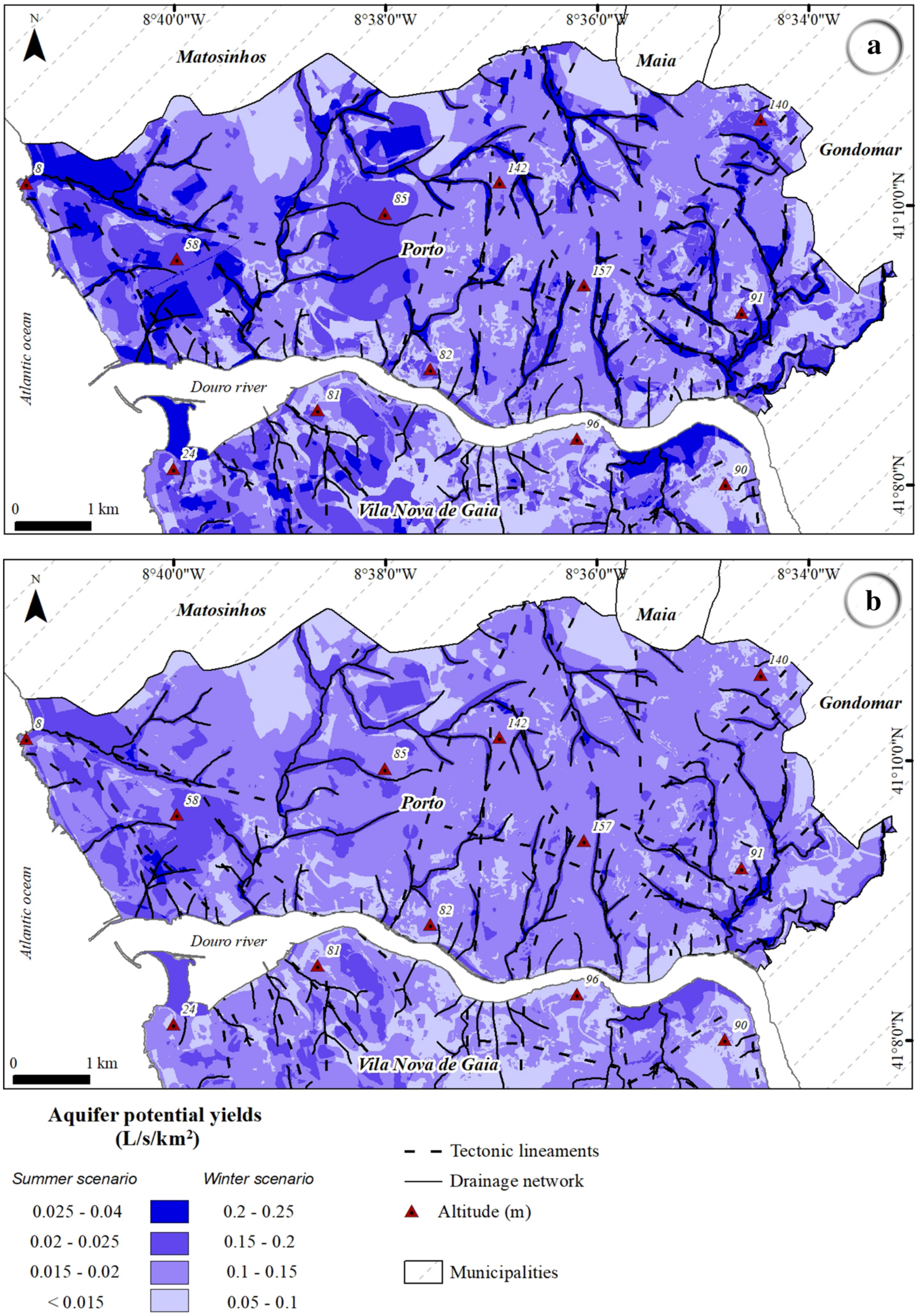
Fig. 7 Urban groundwater recharge rate of Porto urban area: **a** summer scenario; **b** winter scenario and **c** statistical overview for the two scenarios



Urban groundwater recharge rate

Summer scenario		Winter scenario	
Classes	%	Classes	%
6 - 7.1	1.4	6 - 6.8	0.7
5 - 6	8.8	5 - 6	7.8
4 - 5	23.8	4 - 5	23.2
3 - 4	40.4	3 - 4	47.3
1.4 - 3	25.6	1.5 - 3	21.1

c



Aquifer potential yields ($L/s/km^2$)

Summer scenario		Winter scenario	
Classes	%	Classes	%
0.025 - 0.04	13.3	0.2 - 0.25	0.9
0.02 - 0.025	24.5	0.15 - 0.2	19.2
0.015 - 0.02	43.3	0.1 - 0.15	62.8
< 0.015	19.9	0.05 - 0.1	17.0

c

Fig. 8 Shallow aquifer potential yields of Porto urban area: **a** summer scenario; **b** winter scenario and **c** statistical overview for the two scenarios is similar for the summer and winter scenarios, 3.4% and 3.5%, respectively.

In the summer scenario, 40.4% of the area has a recharge rate of 3–4%. Nevertheless, classes 1.4–3% and 4–5% represent in total 49.4% of the area. The highest rates (5–7.1%) occur where the density of tectonic lineaments and the drainage density are higher.

Concerning the winter scenario, the class 3–4% represents 47.3% of this urban area. Moreover, the classes 1.5–3% and 4–5% have an important cartographic expression, which represent 44.3% of the study area. The rest of the area (8.5%) has a higher recharge rate (5–6.8%).

Figure 8 shows the evaluation of shallow aquifer potential yields (L/s/km^2). In the summer scenario, the minimum, maximum and median values are 0.01, 0.04 and 0.02 L/s/km^2, respectively. A significant part of the area (43.3%) has very low potential yields, in the range 0.015–0.02 L/s/km^2. It is possible to highlight the class 0.02–0.025 L/s/km^2, corresponding to 24.5% of the area, as well as the class < 0.015 L/s/km^2, equivalent to 19.9% of the area. The higher class represents 13.3% of the urban area and is located at areas of higher permeability (porous media) and valleys. Regarding the winter scenario, the minimum, maximum and median values are 0.05 L/s/km^2, 0.23 L/s/km^2 and 0.13 L/s/km^2, respectively. Most part of the urban area (62.8%) has a low potential yield, 0.1–0.15 L/s/km^2.

Ferreira da Silva (1889) estimated, in the Summer of 1887, to the Porto city flow rates ranging 0.6–3.3 L/s. In addition, Fontes (1908) stated a value of 5.8 L/s for the total flow of the Paranhos and Salgueiros spring sites (details in Afonso et al. 2010, 2016). COBA (2003) and Afonso (2011) pointed out flow rates ranging 0.7–3.1 L/s to the Porto granitic rocks. These values are coherent with the estimated values in the current study.

Conclusions

Urban groundwater systems are complex and affected by other components of the natural and human environment. The impact of climate variability on urban groundwater is highly debated. In addition, recharge is often the most problematic parameter to assess in urban environment. An appropriate assessment of urban groundwater includes the quantification of the infiltration and recharge, as well as the vulnerability of the numerous sources.

The evaluation of intrinsic vulnerability with four complementary methods permitted to categorize this region on a moderate to high vulnerability scenario that should be enhanced by the multiple potential contamination sources widespread in the area. The delineation of potential infiltration zones and groundwater recharge in Porto urban area was conducted applying GIS techniques which provided an effective methodology in terms of time, effort and cost. GIS-based mapping is an exceptional tool for the assessment of the spatial distribution of key parameters which control the urban groundwater infiltration. Geology, morphotectonics, slope, land use/cover and water supply systems have a key role on the description of the IPI-Urban and on the delimitation of favourable areas of direct groundwater recharge.

In Porto urban area, a moderate to low infiltration potential (IPI-Urban) is predominant, groundwater recharge rates are in the range 3–4%, and shallow aquifer potential yields are very low, generally, as low as 0.5 L/s/km^2. The resultant suitability maps and the multidisciplinary methodology employed in this study can be useful in other urban areas with appropriate modifications and can serve as a guideline for future urban water management projects.

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