ORIGINAL ARTICLE

Groundwater recharge in urban areas (Porto, NW Portugal): the role of GIS hydrogeology mapping

Maria José Afonso[1,2] · **Liliana Freitas**[1] · **Helder I. Chaminé**[1,2]

Abstract

A delineation of groundwater potential zones was performed and an urban infiltration potential index (IPI-Urban) was proposed. The pilot site was the Paranhos and Salgueiros water galleries and surroundings in Porto City (NW Portugal). An integrated approach combining hydrogeomorphology and GIS was developed applying multiple layers of information (tectonic lineaments, hydrogeotechnical units, slope, drainage, land use, sewage and stormwater networks, water supply system and rainfall). Different ranks were assigned to thematic layers and classes received different weights according to their contribution to define groundwater potential areas using the AHP methodology. Two scenarios, Summer and Winter, were computed. 81% of the region is covered by urban and industrial areas and streets. Three areas were identified for major potential direct groundwater recharge (SE of Arca d´Água site, E-SE of Burgães site and W-NW of Lapa site). A Moderate to Low IPI-Urban prevails, and the High and Very high IPI-Urban appear mainly along the three cited valleys. A low to very low recharge was estimated, with less than 50 mm/year and 6% on the Winter scenario. Aquifer potential yields in the Winter scenario are in the range of 1–2 L/s/km^2. The IPI-Urban is a valuable tool for integrated water resources management in urban areas.

Keywords Urban recharge · Groundwater · IPI-Urban · GIS mapping · NW Portugal

Introduction

In the context of climate change, severe climate variability and population growth, increase in water demand, depletion of available water resources, and supply variability require the increase of water resources and consequently the introduction of new research strategies and policies into

This article is part of the special issue on Sustainable Resource Management: Water Practice Issues.

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the present urban water management systems (Rathnayaka et al. 2016). Urban development has a profound impact on hydrological systems (Schirmer et al. 2013; Howard 2015; Afonso et al. 2016). One of the key components of the urban water cycle, which is crucial to integrated water resources management, is groundwater recharge.

Recharge takes place when, after infiltration into the soil, water percolates across the unsaturated zone and reaches the water table. Total recharge includes four processes, which overlap and are not mutually exclusive (e.g. Massing et al. 1990; Lerner 1997; Garcia-Fresca and Sharp 2005; Wiles and Sharp 2008): direct, indirect, artificial and localised. Direct groundwater recharge may be reduced in urban areas, since the increased impervious surfaces lead to a decrease in evapotranspiration, increased runoff and limit the rain recharge (e.g. Lerner 2002; Sharp 2010). Besides, other factors decreasing recharge include the infiltration to sewer, water pipes and storm sewers, and the extraction and export to other basins (e.g. Lerner 1990; Hibbs 2016). Direct recharge occurs mostly in unpaved areas and, on a smaller scale, through the cover generally recognised as impervious

(e.g. asphalt, cement, and brick; Wiles and Sharp 2008; Hibbs and Sharp 2012).

Several features mark the occurrence and movement of groundwater, including geomorphology, lithology, weathering degree, geological structures, porosity, slope, drainage patterns, landform, land use/land cover, and climate. Moreover, urban underground can be referred as an "urban karst", since it comprises a complex system of man-made infrastructure, such as trenches, tunnels, and other buried structures that modify the pre-urban porosity and permeability structure in a manner like natural karst systems (Sharp et al. 2001).

Focusing on flow in urban areas should be the first step for a better understanding of the quantitative and qualitative influence of underground structures on groundwater, and the cumulative impacts of underground structures must be assessed at the decision-making level and regarding hydrogeological constraints (Attard et al. 2016).

Along with other computer-based tools, recent years were full of major advances in GIS, remote sensing and mapping techniques, making them a valuable tool for several sciences, such as groundwater management. The integrated use of these techniques as a vanguard tool is a time and cost-effective means to assess and manage groundwater resources (e.g. Chowdary et al. 2003; Jaiswal et al. 2003; Jha et al. 2007; Yeh et al. 2009; Ballukraya and Kalimuthu 2010; Jha 2011; Teixeira et al. 2013, 2015; Chaminé 2015; Chaminé et al. 2015, 2016). The multicriteria approach, using several information layers, has been greatly enhanced by GIS analysis, and is applied to different water management areas, such as infiltration, vulnerability, or groundwater flow modelling studies (Ettazarini 2007). GIS technology can be very useful

to delineate groundwater infiltration and recharge potential zones, to combine the factors of groundwater recharge potential, and to provide proper weight relationships (e.g. Krishnamurthy et al. 1996; Sener et al. 2005).

This study attempts to define urban groundwater potential zones by using integrated hydrogeomorphology and geographic information systems (GIS) for a pilot area in Porto City. An innovative urban infiltration potential index (IPI-Urban) is proposed for the development of a rational model for groundwater potential in urban environments. Several layers of information, such as tectonic lineaments, hydrogeotechnical units, slope, drainage, land use, sewage network, stormwater network, and water supply system and rainfall, were integrated with weighted overlay in GIS. The study results may be used to formulate an efficient groundwater management plan for the sustainable utilisation of urban water resources.

Porto urban area and the springs of Paranhos and Salgueiros

Porto City is located in the NW Portugal and has been settled on the granitic hill slopes of Douro River banks, adjacent to the Douro River mouth and the Atlantic Ocean (Fig. 1). Porto City is one of the oldest cities in Europe, its history dates back at least to the sixth century, since the days of the Suevians, and became an important metropolis in the twelfth century (de Oliveira Marques 1972). Porto City has an area of 41.3 km^2 and a population of 237,559 inhabitants (INE 2011).
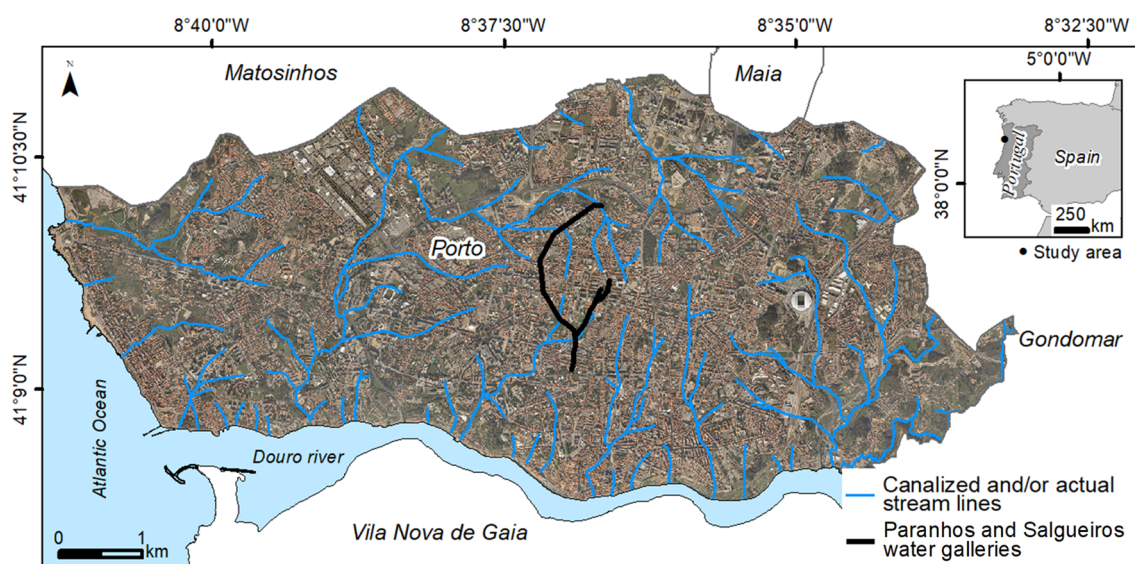

Fig. 1 Regional setting of Paranhos and Salgueiros water galleries (Porto, NW, Portugal)

Porto City has a temperate climate, with a dry and warm summer (Köppen climate classification Csb). The average annual temperature is 15.2 °C. The region has a water deficit from June to September, particularly in July and August. The average annual rainfall is 1236.8 mm/year, reaching 181 mm in December (the wettest month) and 20.4 mm in July (the driest month), (IPMA 2018).

The water supply of Porto City was held through fountains fed by several springs (e.g. Bourbon e Noronha 1885; Carteado Mena 1908; Fontes 1908; Chaminé et al. 2014; Freitas et al. 2014; Afonso et al. 2016 and references therein) for more than six centuries. More than 60 water galleries were excavated throughout centuries to transport water from these springs. Paranhos and Salgueiros water galleries were two of the main galleries. The principal gallery is nearly 3.2 km long and stands at a maximum depth of −20 m below ground level.

The regional hydrogeologic units described in Porto City correspond to the main geological features (e.g. Afonso et al. 2007). Alluvia and other fluvial and marine deposits, mainly constituted by sandy, gravely, silty and clayey sediments, constitute the most important porous media. Yet, since these deposits are generally of limited extent and their thicknesses are usually less than 6 m, they represent shallow aquifers with lesser significance (COBA 2003). The fractured media comprise granitoid rocks, mainly granites and gneisses, and metasedimentary rocks, like micaschists, schists, and metagraywackes. Granitic rocks dominate the study area, predominantly the two-mica, medium to fine grained facies, the so-called "Porto granite" (Almeida 2006). The granitic substratum is, generally, weathered to different grades, from fresh rock to residual soil in short distances, showing highly variable conditions, resulting in arenisation and kaolinisation, which may reach depths of more than 30 m (e.g. Begonha and Sequeira Braga 2002; Gaj et al. 2003). These residual soils play a significant role in the local aquifer recharge (Afonso et al. 2007). At a local scale, the hydrogeotechnical units in the surrounding area of Paranhos and Salgueiros water galleries are (Afonso et al. 2010a; Chaminé et al. 2010):

- Alluvial deposits—consist mainly of sands and silts with low to moderate permeability (< 2 m/day); these deposits outcrop but were not identifiable inside the galleries, perhaps because of their small thickness (< 6 m) and, mostly, by the fact that in the areas where the galleries cross the alluvia, the galleries are reinforced by stone walling and/or concrete.
- Saprolite soils—most of these are kaolinitic silty sands firmly related to the Porto granite (Begonha and Sequeira Braga 2002) with very low permeability (< 0.1 m/day);
- Porto granite—this unit is intersected by crushed quartz veins ranging from millimetres to several cen-

timetres in thickness and occurs weathered to different grades (ISRM 1978, 1981), from fresh rock to slightly weathered (W_{1-2}) to highly weathered (W_{4-5}), but predominantly, moderately weathered (W_3). Its fracturing intercept degree (Afonso et al. 2010a, b) is, dominantly, moderate (F_3) to wide (F_{1-2}). The permeability is low to moderate (< 1 m/day).

Materials and methods

The basic data collection techniques of geology, geomorphology and hydrogeology have been applied in this study (e.g. Assaad et al. 2004; Dykes et al. 2005; Peterson 2009; Scesi and Gattinoni 2009; Smith et al. 2011; Gustafson 2012; Norbury 2016). The terminology and recommendations of the Geological Society Engineering Group (GSE 1995), the Committee on Fracture Characterisation and Fluid Flow (CFCFF 1996), and the International Society for Rock Mechanics and Rock Engineering (ISRM 1978, 1981, 2007, 2015) were followed. A geodatabase was created in a GIS environment and the methodology adopted within the study area is summarised in the flowchart shown in Fig. 2.

The data, collected from several sources and at different scales, were divided in two main groups, namely the vector data (e.g. contour lines, stream lines, land use) and raster data (e.g. satellite imagery, aerial photography, geological map). This geodatabase allowed the creation of several thematic maps, to assess the spatial distribution of all the factors controlling groundwater infiltration in urban areas.

The identification of the explaining factors was compiled and revised from the reference bibliography (e.g. Krishnamurthy et al. 1996; Babar 2005; Jha et al. 2007, 2011; Yeh et al. 2009; Teixeira et al. 2013, 2015). The relative weight and score for each factor was calculated using the analytical hierarchy process (AHP), a theory and methodology for relative measurement, where the main interest is to know the proportions between quantities, rather than the exact measurement of them (e.g. Saaty 2008, 2012). The inner scores were mainly assessed from data obtained from fieldwork. According to Brunelli (2015) and Mu and Pereyra-Rojas (2017), the relative measurement theory suits particularly well problems where the best alternative must be chosen. Besides, when attributes of alternatives are intangible, it is difficult to create a measurement scale and the analysis is simplified using relative measurements. The final scope of the AHP is to use pairwise comparisons between alternatives as inputs, which compare all the criteria to one another, to estimate a rating or weighting of each of the criteria that describes the importance of each of these criteria in contributing to the overall objective. Several papers have been published in recent years applying the AHP methodology to groundwater issues, namely, Kim et al. (2009), Agarwal

Fig. 2 Flowchart showing data and methods employed for the present study
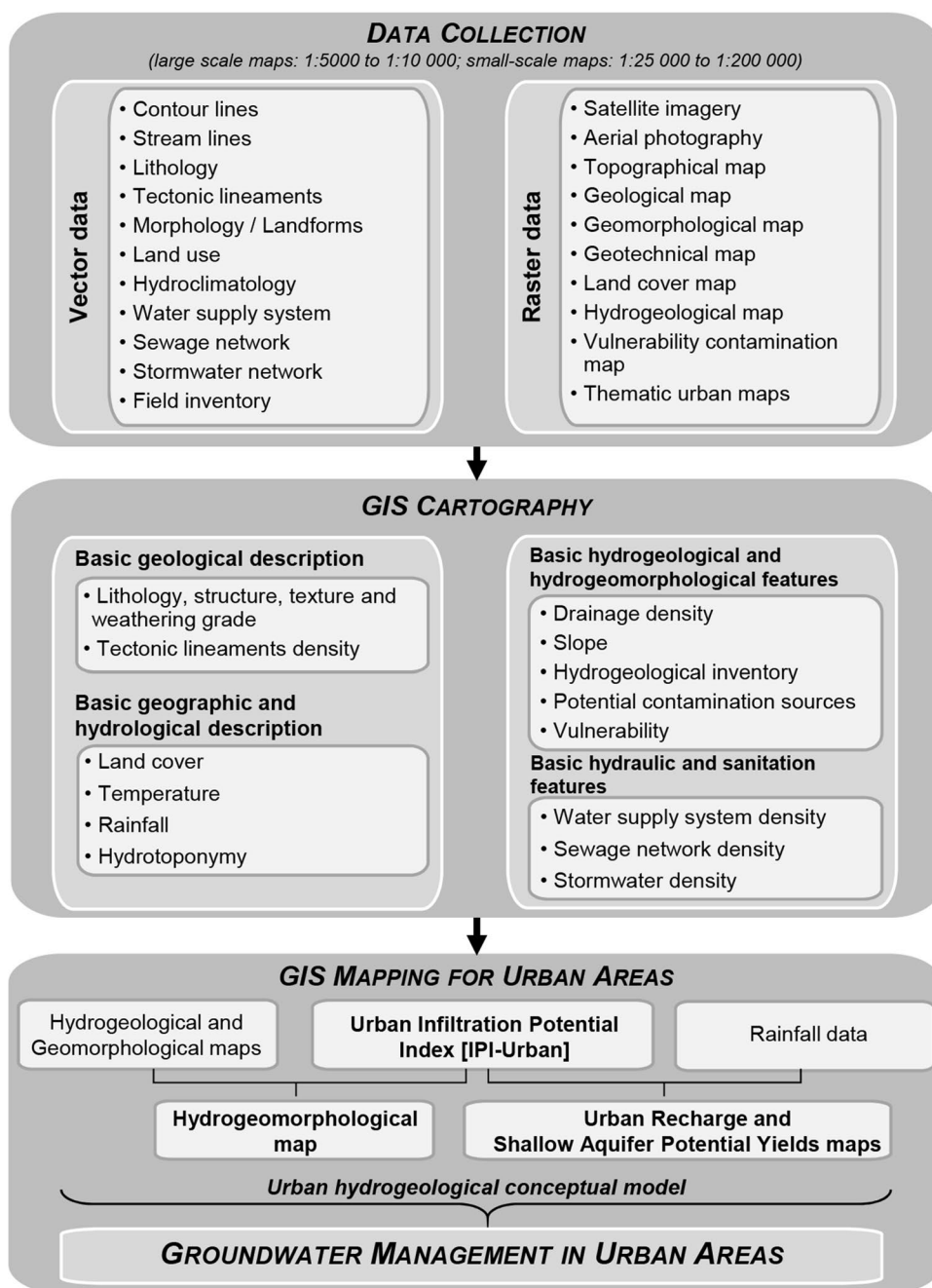
et al. (2013), Şener and Davraz (2013), Teixeira et al. (2013, 2015), Şener and Şener (2015), Pani et al. (2016), Sahoo et al. (2016), Huang et al. (2018), and Şener et al. (2018).

The input maps related to the basic geological description, the geographical and hydrological characteristics, the hydrogeological and hydrogeomorphological features, and the hydraulic and sanitation features (see Fig. 2) have been used, along their specific weight, to calculate the urban infiltration potential index (IPI-Urban). The grid data structure was used with a pixel of 1×1 m^2. The result of this GIS analysis is a map, which reflects the spatial variation of the infiltration potential, ranging from 0 to 100, where the highest values represent a combination of favourable characteristics in most explaining factors.

In this study, two scenarios were computed, Summer and Winter, and the weight of the explaining factors was changed accordingly (Table 1), along with all the immutable characteristics of the study area (tectonic lineaments density, hydrogeotechnical units, slope, drainage density, land use areas, sewage network density, stormwater network density and water supply network density). Since the study area is hot and dry in the Summer ($P < 21$ mm in the warmer

Table 1 Criteria and weights given for the two scenarios examined in the study

Criteria	Weight (%)	
	Summer	Winter
Tectonic lineaments density	14.6	16.2
Hydrogeotechnical units	25.8	25.1
Slope	15.3	13.2
Drainage density	5.7	4.7
Land use areas	22.1	15.8
Sewage network density	6.3	5.9
Stormwater network density	n.a.	5.9
Water supply system density	10.2	13.2

n.a. not applicable

month), the Summer scenario was computed without the stormwater network density map. The resulting maps were then overlaid with the geomorphological map and other hydrogeological inventory features, to produce an hydrogeomorphological map for this urban area.

To estimate the urban recharge, an analysis of the average monthly rainfall was performed. The dry period is from June to September and the rainfall value used for Summer scenario was the total precipitation for these 4 months, i.e. 165.1 mm. For the Winter scenario, the remaining months, corresponding to the wet period, were used with a total precipitation of 1071.7 mm. Then, an initial recharge value of 8% was used, according to regional studies (e.g. Afonso et al. 2007; Afonso 2011). The groundwater recharge (mm/year) was obtained multiplying each pixel of the IPI-Urban map by the precipitation considered for each scenario. Additionally, the groundwater recharge rate (%) was achieved dividing each pixel of the groundwater recharge map (mm/year) by the effective precipitation for each scenario, i.e. 8% of the total precipitations. To assess the aquifer potential yields map, a basic mathematical operation was performed to convert the units of groundwater recharge from mm/year to L/s/km^2.

Results and discussion

The description of all eight thematic layers—tectonic lineaments density, hydrogeotechnical units, slope, drainage density, land use areas, sewage network density, stormwater network density, and water supply system density—along with their spatial distribution in the study area is presented in this section (Figs. 3, 4).

Regarding tectonic lineaments, most of the area (ca. 93%) has a density of 7–14 km/km^2, the highest density being 14–21 km/km^2, located around Burgães and Lapa sites.

Hydrogeotechnical units play a key role in groundwater occurrence in this area. Highly weathered (W_{4-5}) granite is the most representative (ca. 55%), while fresh to slightly weathered (W_{1-2}) granite with wide spaced fractures (F_{1-2}) and moderately weathered (W_3) granite with moderately close spaced fractures (F_3) occupy in total nearly 30% of the area.

About slope, most of the area has a gentle to very gentle slope (< 5°, ca. 51%) to moderate to strong slope (5–15°, ca. 40%); the highest gradients, > 25°, are located around Lapa site.

Drainage density is frequently below 3 km/km^2 (ca. 77%) and the highest densities are sited around Arca d'Água and Lapa sites.

Land use plays a very important role in this area. Urban and industrial areas cover the larger part (ca. 68%). Besides, streets correspond to 12.7% of the study area and among these 7.8% correspond to concrete/bituminous pavements and 4.9% to granite paving blocks. However, green spaces (public gardens and backyards) and agricultural sites represent nearly 19% of the total area. This means that, in the surrounding area of Paranhos and Salgueiros water galleries, surfaces of low to very low permeability prevail that are responsible for the decrease in direct groundwater recharge.

Concerning the sewage network, most of the area has a density of 14–21 km/km^2 (ca. 62%), and densities of 7–14 km/km^2 occupy the second position (ca. 35%).

For stormwater network, densities < 5 km/km^2 are prevalent (ca. 58%) in the area, while densities of 5–10 km/km^2 are the second most frequent (ca. 32%). The highest values are located to the east and southwest of Lapa site.

Finally, the dominant water supply system classes are 21–28 km/km^2 (ca. 42%) and 14–21 km/km^2 (ca. 36%).

To identify the potential areas of direct groundwater recharge, the pervious cover in the area was assessed. In cities, direct recharge takes place by percolation into unpaved areas, and to a lesser extent through "impervious" surfaces. Consequently, the intersection between green spaces and agricultural sites with the hydrogeotechnical units was performed. Therefore, considering that alluvial formations generally have higher permeability than granite, the primary zones will correspond to those in which alluvia and green and/or agricultural spaces co-occur. However, it would be too simplistic to consider only these areas, so other minor areas have also been considered, specifically, green and agricultural spaces covering the granite (Fig. 5).

Hence, considering these areas, as well as the geomorphological characteristics of this region, namely its location in the western border of the highest plateau of Porto City, it is possible to verify that the potential areas of direct groundwater recharge are located relatively close to the water galleries, namely along the following valleys: (1) NNW–SSE alignment, located SE of Arca d'Água site; (2)
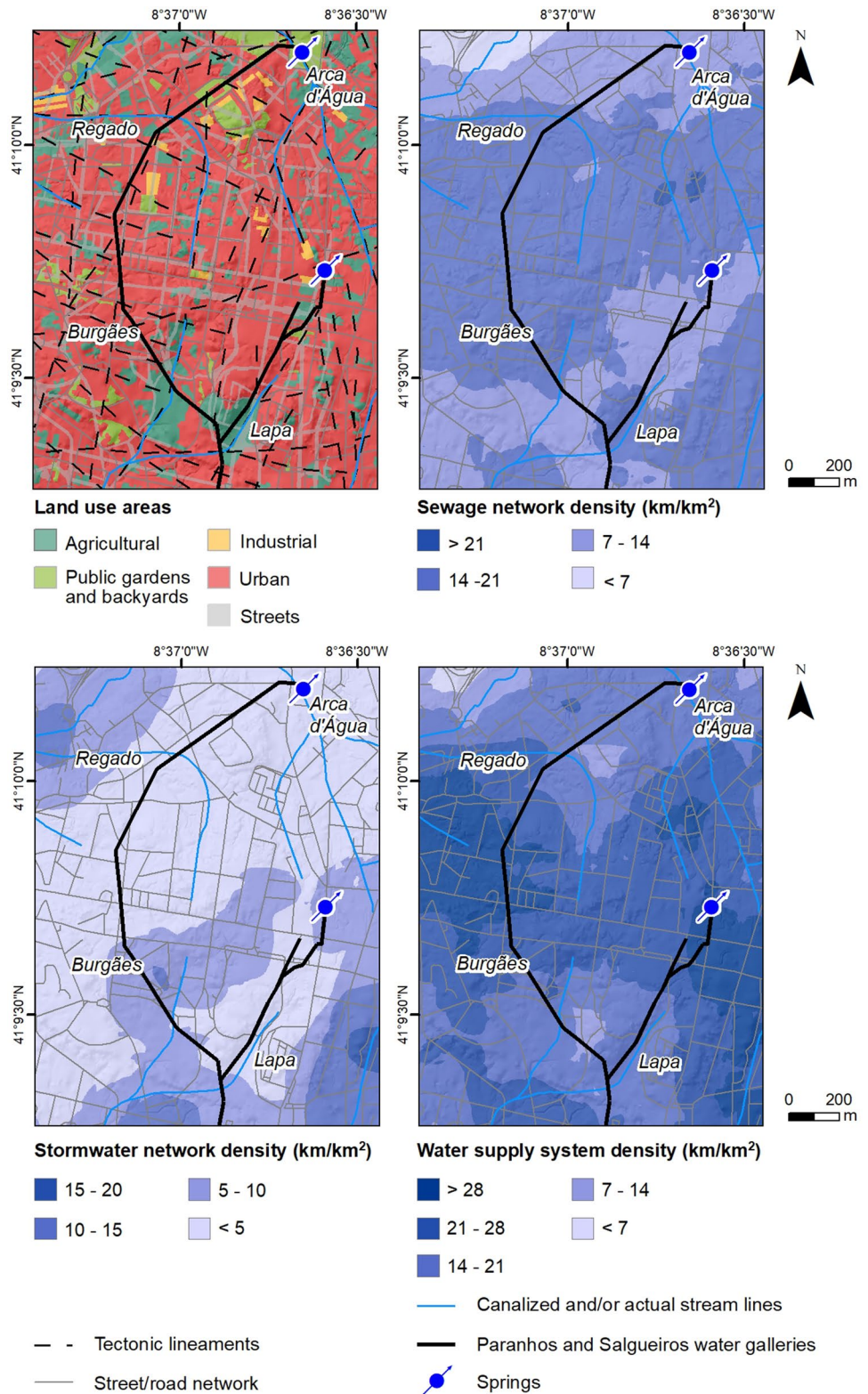
Fig. 3 Tectonic lineaments density, hydrogeotechnical units, slope, and drainage density in the study area
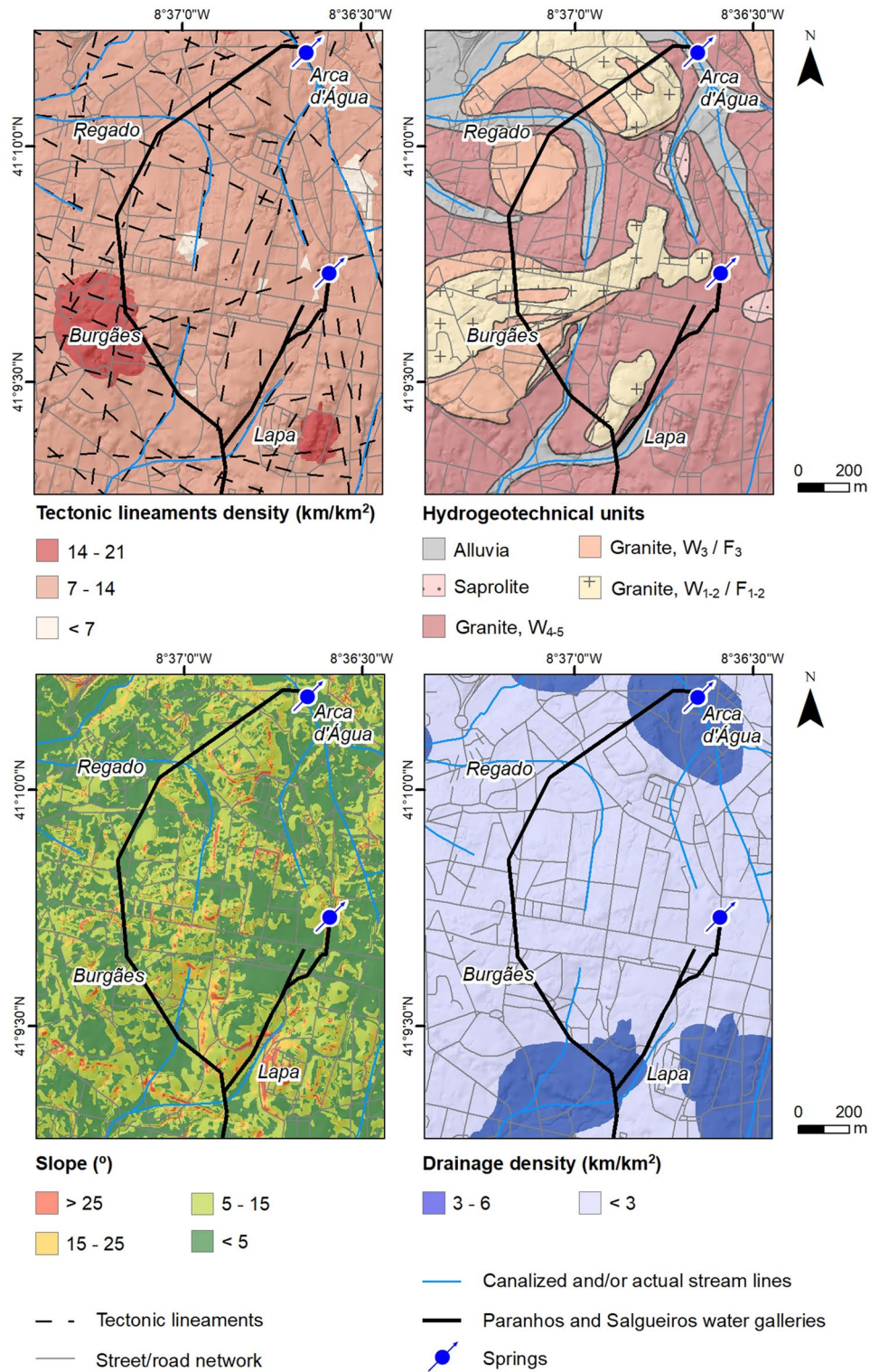
NNE–SSW orientation, located E–SE of Burgães site; and (3) NE–SW direction, located W–NW of Lapa site, where Salgueiros water gallery is placed and where the junction of this gallery with Paranhos water gallery is located.

In addition, these zones overlap tectonic lineaments, which may act as privileged pathways of precipitation through the granitic rock mass. A proportion of the impervious cover should be treated as permeable, as

Fig. 4 Land use areas, sewage network density, stormwater network density, and water supply system density in the study area

Land use areas
- Agricultural
- Public gardens and backyards
- Industrial
- Urban
- Streets

Sewage network density (km/km²)
- \> 21
- 14 -21
- 7 - 14
- \< 7

Stormwater network density (km/km²)
- 15 - 20
- 10 - 15
- 5 - 10
- \< 5

Water supply system density (km/km²)
- \> 28
- 21 - 28
- 14 - 21
- 7 - 14
- \< 7

- — - Tectonic lineaments
- —— Street/road network
- —— Canalized and/or actual stream lines
- —— Paranhos and Salgueiros water galleries
- ● Springs

some infiltration takes place through pavements. Wiles and Sharp (2010) consider that urban pavements are permeable and estimate that 21% of mean annual rainfall is available as potential recharge. Moreover, green spaces and agricultural sites are also key areas for the artificial recharge, since they are irrigated, particularly in the summer period. Finally, these potential areas of direct groundwater recharge should be added to the areas of localised

Fig. 5 Potential areas of direct groundwater recharge in the surroundings of Paranhos and Salgueiros water galleries
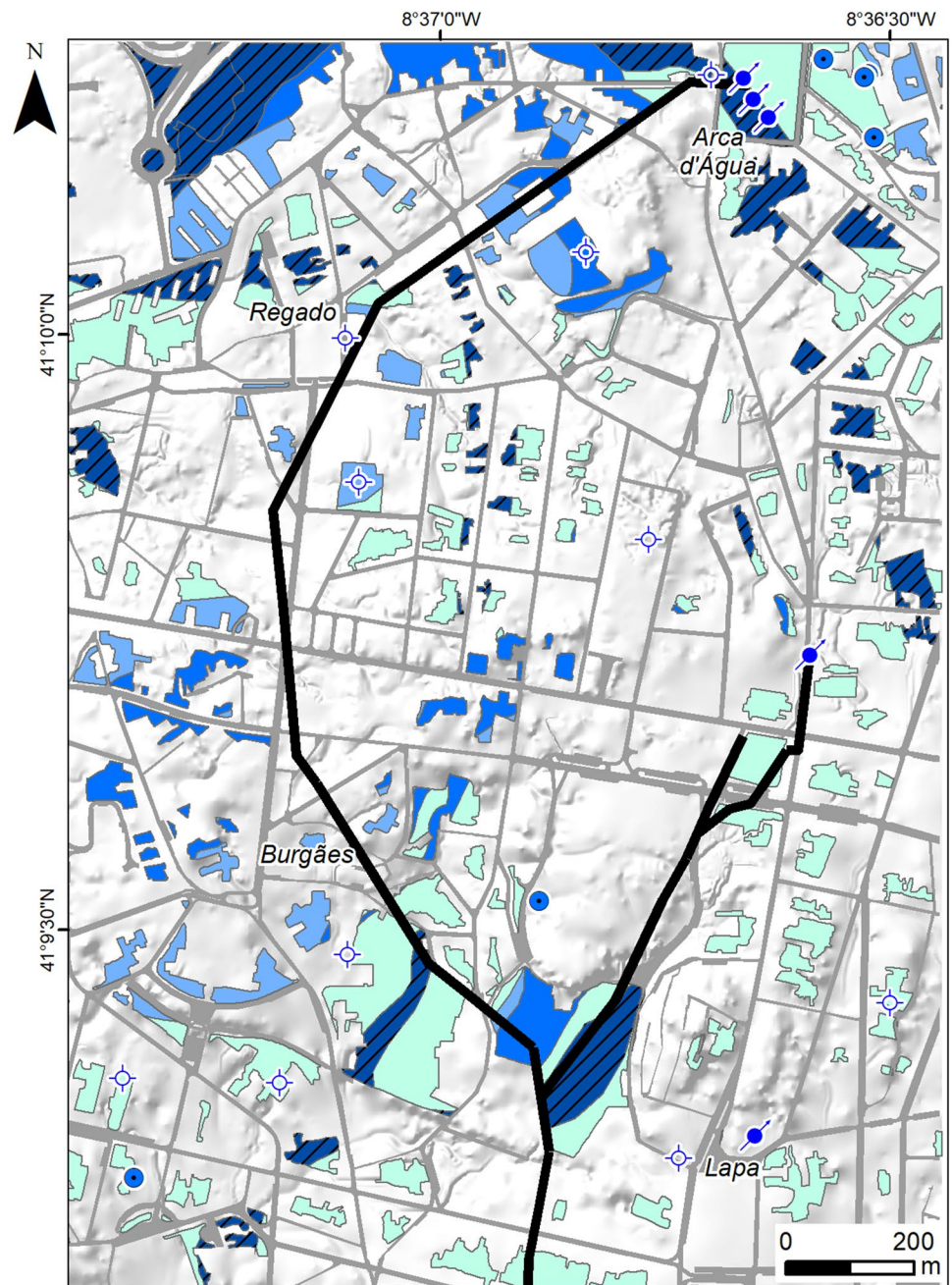
Potential areas of direct groundwater recharge

Principal

Green and agricultural areas, with alluvia

Secondary

Green and agricultural areas with granite W_{1-2} / F_{1-2}

Green and agricultural areas with granite W_3 / F_3

Green and agricultural areas with granite W_{4-5}

Hydrogeological inventory

- Boreholes
- Fountains
- Springs
- Tectonic lineaments
- Street/road network
- Paranhos and Salgueiros water galleries
- Canalized and/or actual stream lines
- Contour lines

recharge, corresponding to the several non-tight ventilation shafts of the water galleries, as well as the artificial recharge, spread throughout the region through the stormwater and sewage networks and the water supply system.

Considering the hydrogeological inventory, among the identified five springs, three are in the potential areas of direct recharge and two are close to secondary potential areas of direct recharge. Besides, these springs are also correlated with the tectonic lineaments (see Figs. 3, 4). Moreover, these springs are shallow groundwater that respond quickly to precipitation events (Afonso et al. 2010b). Therefore, although springs represent areas of groundwater discharge, these springs are situated near the local recharge areas.

The urban infiltration potential index (IPI-Urban) was calculated for Summer and Winter scenarios (Fig. 6). For a better understanding of the distribution of infiltration potential in the study area, one must have in mind the combination of criteria with greater weights (cf. Table 1). Therefore, about 80% of the total weight corresponds, in both scenarios, to hydrogeotechnical units, tectonic lineaments density, slope, and land use areas. Consequently, it is possible to achieve that in both scenarios, a Moderate to Low (40–60) IPI-Urban is prevalent, corresponding to 67% and 74% of the entire study area, for the Summer and Winter scenarios, respectively. Moreover, the High (60–80) and Very high (80–100) indexes, particularly the first one, arise mainly along the three valleys previously mentioned. These geomorphologic

Fig. 6 Urban infiltration potential index (IPI-Urban) for Summer and Winter scenarios in the surroundings of Paranhos and Salgueiros water galleries; I, II, and III: inset detailed maps of the Summer scenario for Arca d´Água, Salgueiros and Lapa sites
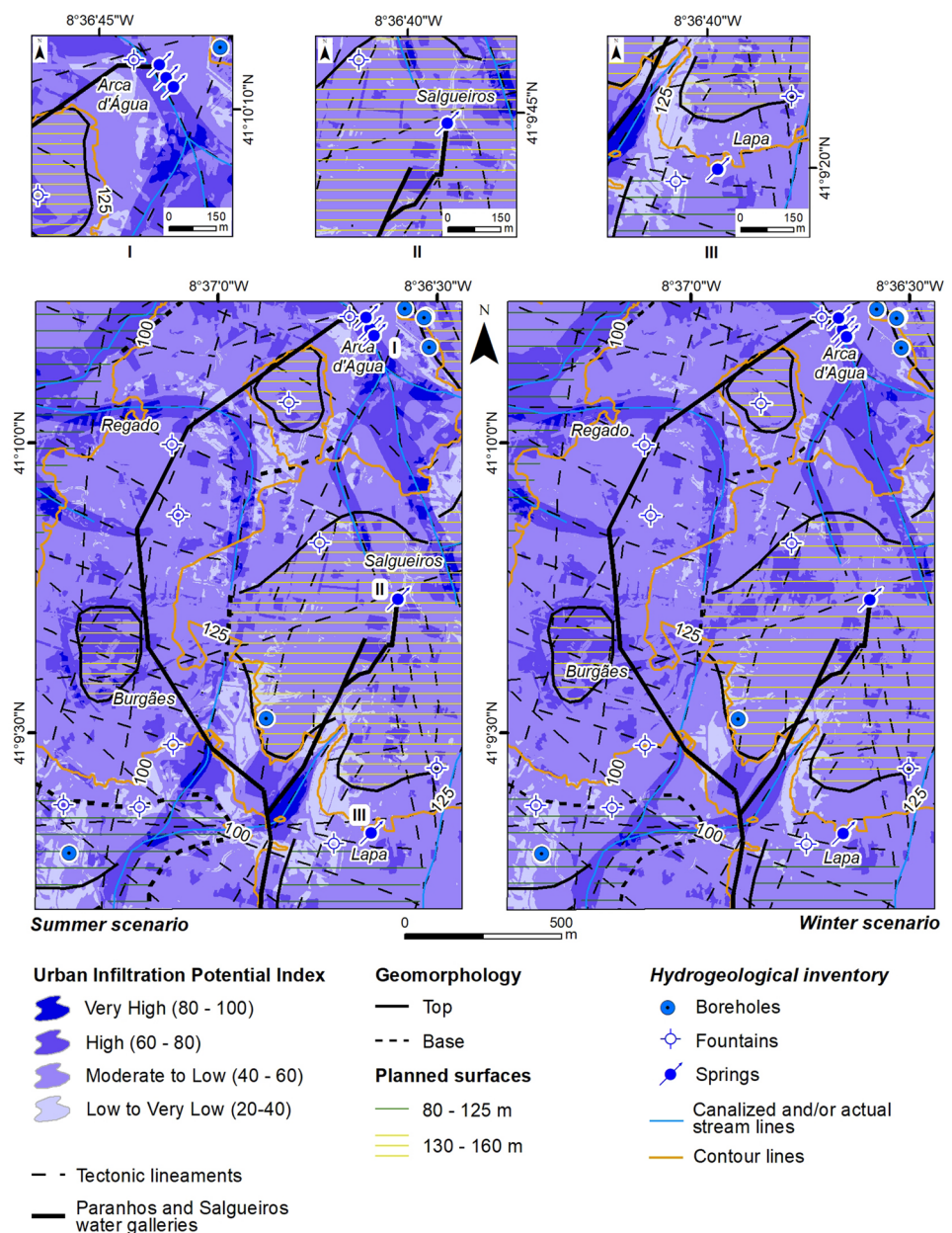
features correspond mostly to alluvial formations, usually with moderate to gentle gradients (< 15°), where green spaces and/or agricultural areas are present. The highest values are most frequent in the Summer scenario, since the land use areas criterion has a higher weight than in the Winter scenario. Additionally, other areas with a high index may be identified, corresponding to the fractured granite W_{1-2}, also with low gradients (< 15°) and, in the case of Burgães site, where one of the highest densities of tectonic lineaments arises.

Considering the hydrogeological inventory, it is possible to see that three of the springs are in areas of High to Very High infiltration potential, while two are in areas of Moderate to Low infiltration potential.

Considering the evaluation of urban recharge, this component was evaluated in mm/year and as a percentage of precipitation for the Summer and Winter scenarios (Fig. 7).

Most of the area has a low to very low recharge, especially in the Summer scenario. Values under 8 mm/year and under 50 mm/year are estimated in 77% of the area in the Summer scenario, and 74% of the area in the Winter scenario and these numbers correspond to recharge percentages of less than 1% and 6%, respectively, in the Summer and Winter scenarios. The highest values befall primarily around alluvial formations and secondly on the fractured granite W_{1-2} to W_3. Nevertheless, in the surroundings of Lapa site, particularly in the Winter scenario, higher values occur, although the outcropping granite is W_{4-5}. This should be ascribed to higher densities of tectonic lineaments, drainage, sewage and stormwater networks, and water supply system. Garcia-Fresca and Sharp (2005) reveal that in Austin City (USA), a significant indirect recharge occurs and that nearly 8% of Austin water main flow is lost to become recharge. Moreover, Vázquez-Suñé et al. (2005) assume that in Barcelona City (Spain) the main contributors to total recharge are the water supply network losses (22%), the sewage network losses (30%), rainfall, concentrated in the non-urbanised areas (17%), runoff infiltration (20%), and the Besòs River (11%). Additionally, the key role of losses in sewage system on the quality of Paranhos and Salgueiros groundwater system is demonstrated in Afonso et al. (2016).

The evaluation of aquifer potential yields was also carried out for the Summer and Winter scenarios (Fig. 8). In the Summer scenario, 76% of the area has potential yields of less than 0.25 L/s/km² and the median value for the entire area is 0.2 L/s/km². On the other hand, in the Winter scenario, 96% of the area has potential yields in the range 1–2 L/s/km² and the median value for the entire area is 1.4 L/s/km².

The groundwater yields in Paranhos and Salgueiros water galleries were not yet possible to quantify, since the water flows in a gutter pipe, in the floor, and from the ceilings of the galleries.

However, 130 years ago, Ferreira da Silva (1889) presented values evaluated in the summer time (August) of 1887. Flow rates of 288 m³/day (≈ 3.3 L/s) and 54 m³/day (≈ 0.6 L/s) were mentioned for Paranhos spring and Salgueiros spring, respectively. Instead, 19 years later, Fontes (1908) stated a value of 500 m³/day (≈ 5.8 L/s) for the total flow of Paranhos and Salgueiros springs. Moreover, almost 100 years later, COBA (2003) concluded that in 75% of the cases for Porto granite, which may include from residual soils to unweathered rock, flow rates of 0.8 L/s are not exceeded, with mean and maximum values of 0.7 L/s and 3.1 L/s, respectively. It is possible to argue that the mean and the maximum values are similar to those reported by Ferreira da Silva (1889) for the Salgueiros spring and Paranhos spring, respectively. In addition, one of the boreholes of the hydrogeological inventory located to the east of Arca d´Água site has a yield of circa 0.6 L/s (Afonso 2011), which is coherent with the previous estimated values.

Conclusions

Aquifer recharge is often the most difficult parameter to evaluate in urban hydrological environments. The evaluation of recharge in these environments is different from that in natural systems, because recharge sources are totally different and less knowledge is still available. A suitable assessment of groundwater quantity comprises the quantification of overall recharge, as well as water quality assessment of the various sources involved.

GIS techniques have provided an efficient and practical environment for the assessment of the spatial distribution of relevant parameters controlling water infiltration into the soil, percolation in the unsaturated zone, and aquifer recharge in urban areas.

Lithology, tectonic lineaments, slope, land use, and water supply system have a significant role in the definition of the urban infiltration potential index (IPI-Urban) and on the delimitation of potential areas of direct groundwater recharge. A Moderate to Low IPI-Urban is prevalent in the pilot site. Additionally, High and Very high index values validate most of the key areas of direct groundwater recharge. Most of the pilot area has low to very low urban recharge with less than 50 mm/year and less than 6% of precipitation in the wet season. Aquifer potential yields are low in most of the pilot sites and lower than 2 L/s/km². The most important groundwater potential zones are mainly concentrated along the three valleys located SE of Arca d´Água site, E–SE of Burgães site and W–NW of Lapa site, due to their gentle terrain nature, with alluvial formations and the presence of green spaces and/or agricultural areas having relatively high infiltration capacity.

Fig. 7 Urban recharge for the Summer and Winter scenarios in the surroundings of Paranhos and Salgueiros water galleries: **a** mm/year and **b** %
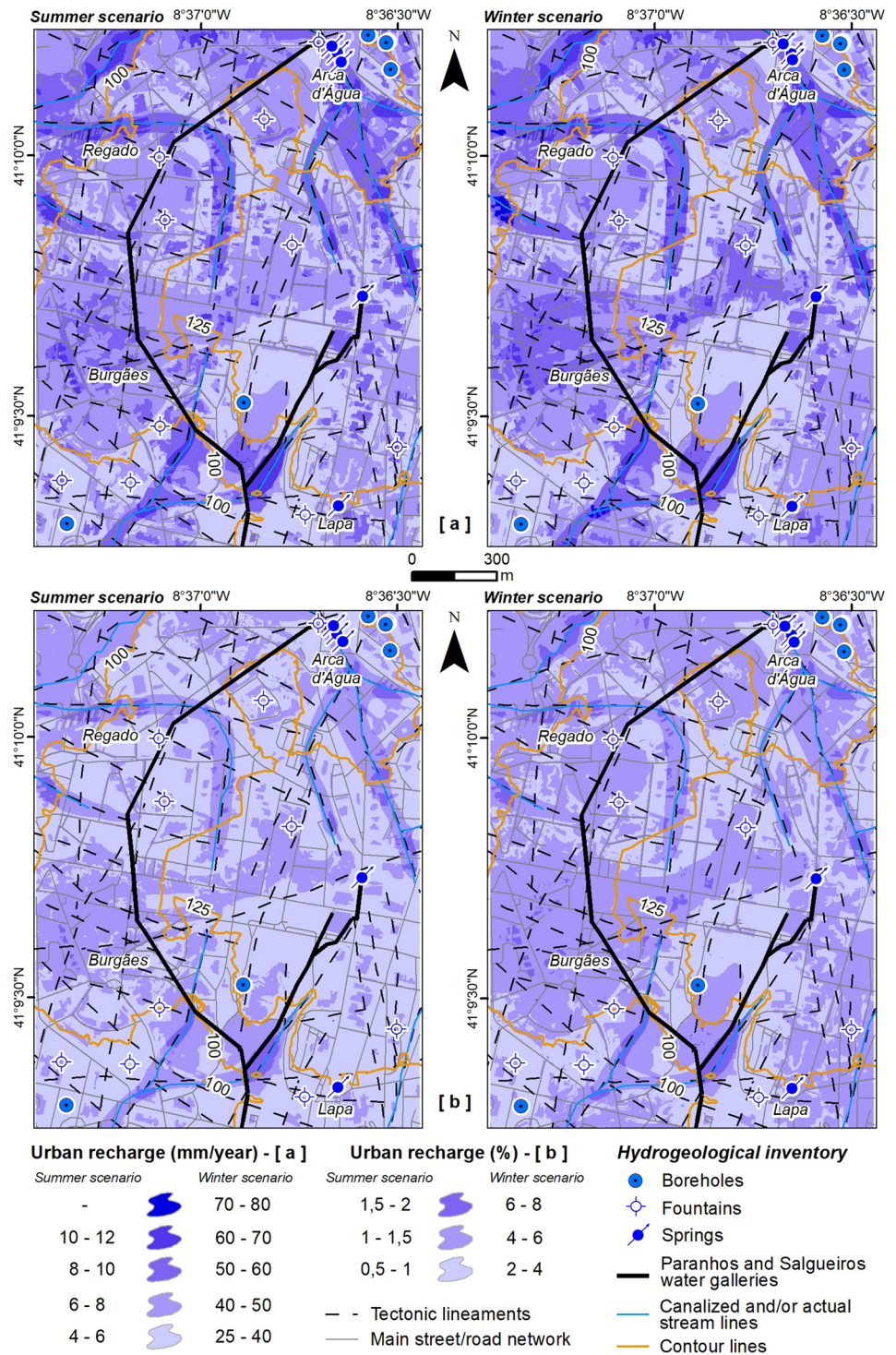
This study can serve as a guideline for planning and implementing future urban groundwater interventions and is broadly applicable to other urban areas to guarantee sustainable groundwater use. It is also a valuable tool that allows policy makers quick decision-making in sustainable water resource management.
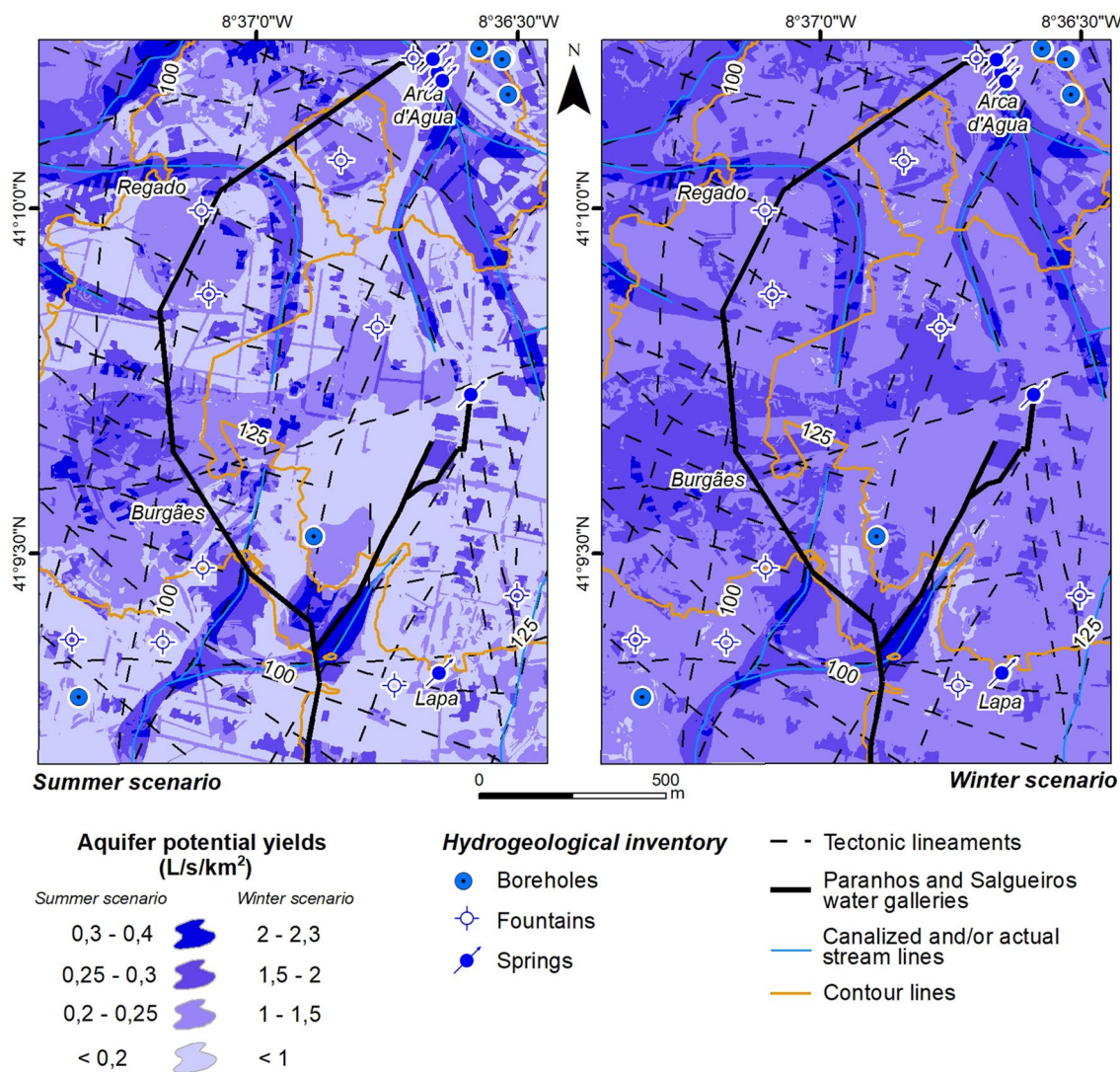
Fig. 8 Aquifer potential yields for the Summer and Winter scenarios in the surroundings of Paranhos and Salgueiros water galleries

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