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Urban Groundwater Processes and Anthropogenic Interactions (Porto Region, NW Portugal)

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Abstract: Groundwater in fissured rocks is one of the most important reserves of available fresh water, and urbanization applies an extremely complex pressure which puts this natural resource at risk. Two-thirds of Portugal is composed of fissured aquifers. In this context, the Porto urban region is the second biggest metropolitan area in mainland Portugal. In this study, a multidisciplinary approach was developed, using hydrogeological GIS-based mapping and modeling, combining hydrogeochemical, isotopic, and hydrodynamical data. In addition, an urban infiltration potential index (IPI-Urban) was outlined with the combination of several thematic layers. Hydrogeochemical signatures are mainly Cl-Na to Cl-SO_4-Na, being dependent on the geographic proximity of this region to the ocean, and on anthropogenic and agricultural contamination processes, namely fertilizers, sewage, as well as animal and human wastes. Isotopic signatures characterize a meteoric origin for groundwater, with shallow flow paths and short residence times. Pumping tests revealed a semi- to confined system, with low long-term well capacities (<1 L/s), low transmissivities (<4 m^2/day), and low storage coefficients (<10^{-2}). The IPI-Urban index showed a low groundwater infiltration potential, which was enhanced by urban hydraulic and sanitation features. This study assessed the major hydrogeological processes and their dynamics, therefore, contributing to a better knowledge of sustainable urban groundwater systems in fractured media.

Keywords: urban groundwater; hydrogeochemistry; hydrodynamics; IPI-Urban; NW Portugal

1. Introduction

Urbanization is the foremost global phenomenon of our time, and groundwater from springs and wells has been a vital source of urban water supply since the first settlements [1]. Urban hydrogeology is a key scientific field, and an understanding of groundwater in urban areas has increased greatly in the last decades. Attention was given to the relationship between urban development and groundwater resources beginning in the 1950s and 1960s of the 20th century, when accelerated growth after the Second World War began to cause significant diversity of hydrological problems. Most of these problems were related to urban runoff and floods, therefore, urban hydrology established itself in an affirmative way [2,3]. Thus, urban groundwater rapidly emerged as a necessary and urgent branch of study. Particularly, after the 1990s of the 20th century, several scientific publications on issues addressing the subject of hydrogeology in urban areas are found, namely [2–22].

The impact of urban development on geological processes, in general, and groundwater systems, in particular, has been highlighted for a long time (e.g., [12,16,23–36]). It is remarkable that only one century ago, 20% of the world population lived in urban areas, whereas, presently, 54% of the world population lives in urban environments [37]. Anthropogenic activity is the major geomorphic agent affecting the Earth's land surface, while urbanization and agriculture are, perhaps, the major processes currently affecting the land (e.g., [7,14,20,23,38–41] and references therein). The need for provision of safe water, sanitation, and drainage systems are key elements which are vital to the understanding and management of groundwater resources in urban environments. Groundwater problems associated with urbanization and urban sprawl include both quantity and quality issues, namely (e.g., [2,42]), subsidence, covering of shallow systems, increased recharge from leaky water ascribed to sewage systems and irrigation return flow, changes in subsurface secondary porosity, permeability from utility systems and other constructions, as well as the effects of imported water resources, saline intrusion, and contamination from point and nonpoint sources. In this context of global anthropogenic activity, groundwater is a key source of urban supply worldwide, and aquifer storage represents a key resource for achieving water-supply security under climate change that will contribute to aggravate these pressures, with decreasing rainfall, as well as longer and more frequent and extended drought periods (e.g., [1,43,44]). Additionally, the impact of the complex system of man-made infrastructures (e.g., sewer, storm sewers, pipes, trenches, tunnels, and other buried structures) and impervious surfaces and or cover areas must be highlighted as anthropogenic disturbances in groundwater media (e.g., [11,42,45–47]).

Integrated multidisciplinary approaches are often required to address the scientific issues involving groundwater resources. In this way, environmental isotopes such as ^{2}H, ^{18}O, ^{13}C, and ^{3}H, can be used as fingerprints to assess some of these groundwater problems and to provide information needed for the rational management of these water bodies (e.g., [48–50]). Furthermore, the delineation of groundwater potential zones (GWPZ's) using remote sensing, geographic information systems (GIS), and geovisualization techniques are effective tools for groundwater exploration and groundwater recharge (e.g., [13,17,18,35,36,51,52]). This approach encompasses the integration of several factors, organized from different geodatabases and a multiparametric approach, which influence the occurrence of groundwater, namely lithology, tectonic lineaments, land use, slope, drainage, precipitation, and urban hydraulics. Nearly half of the world depends on groundwater as the main source of drinking water [53]. However, groundwater is an underexploited resource in many urban areas, due to its invisibility, inadequate management, scientific uncertainty, and political strategies that favor the use of surface waters (e.g., [54–57]).

The main objectives of this study in the Porto urban region (NW Portugal) were:

1. To develop an integrated geoenvironmental assessment of groundwater resources in urban environments using geotechnological capabilities, particularly GIS mapping and geovisualization techniques, and also extensive field and laboratory work;
2. To evaluate groundwater quality and groundwater flow paths, by combining hydrogeochemical and environmental isotopic data and to identify the leading processes responsible for groundwater disrepair;
3. To assess groundwater quantity, by means of pumping test data;
4. To delineate groundwater infiltration potential zones at a regional scale, using the innovative infiltration potential index for urban areas (IPI-Urban) that integrates several layers of information properly weighted and overlaid in a GIS platform; a tool which should improve our understanding of complex urban groundwater recharge processes in future investigations;
5. To refine the regional hydrogeological conceptual model, merging all the data, to improve the understanding of urban groundwater systems in the Porto urban region.

2. Study Area: Land Cover and Hydrogeological Background

The Porto urban region is a densely populated region which includes other cities such as Vila Nova de Gaia, Matosinhos, Maia, and Vila do Conde, in the Porto Metropolitan Area, with about 1.7 million inhabitants [58], (Figure 1). According to the land use map for mainland Portugal [59], most of the investigated region (93.3%) is occupied by the following three classes: urban and industrial areas (41.4%), agricultural areas (28.5%), and forest areas (23.4%). Urban areas are concentrated primarily in the municipality of Porto and in the surrounding municipalities. Agricultural spaces are located mainly in the northern part, especially in the municipality of Vila do Conde. Forest areas are mainly found in the NE, especially to the east of Vila do Conde and in the municipality of Trofa.

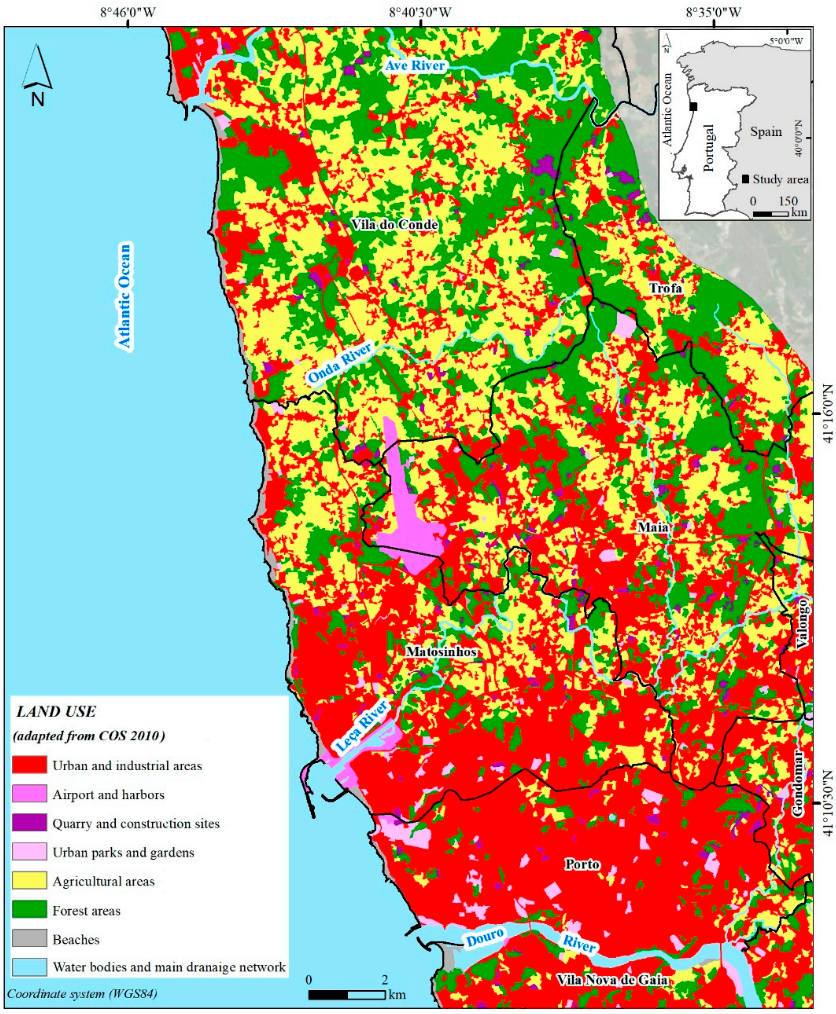


Figure 1. Land use of the urban coastal region between the Municipalities of Vila do Conde and Vila Nova de Gaia (adapted from [59]).

Considering agriculture and farming, the most important food supplies produced in this region are potatoes, vegetables, fruits, and maize, as well as cattle raising, namely bovines. According to [20], the two principal types of fertilization are organic which uses mostly manure, as well as sewage and inorganic. The inorganic fertilizers are mostly composed of nitrogen, phosphorous, potassium, and nitrogen which is the most prevalent. A sprinkler system is the leading irrigation system.

This region is drained by the following four major streams: the Ave River, in the north; rivers Onda and Leça in the centre; and Douro River, in the south. Located close to the Atlantic Ocean, this region has a temperate climate with dry and mild summers (Köppen climate classification Csb), with a mean annual precipitation around 1200 mm and a mean annual air temperature of 14 °C. There is a water deficit from June to September, mainly in July and August [60–62]. The availability of groundwater resources is reflected by these climatic conditions, along with geologic and morphotectonic features. The regional geological framework comprises a crystalline fissured basement of highly deformed and overthrust Late Proterozoic/Palaeozoic metasedimentary and granitic rocks. The post-Miocene sedimentary deposits frequently cover the bedrock [63–65] and references therein. The morphotectonic background includes a littoral platform characterized by a regular planation surface dipping gently to the west, ending around 100 m a.s.l [66]. The Ave, Leça, and Douro rivers have incised valleys that cross the flatness of this morphological surface, suggesting a regional tectonic control. The main regional hydrogeologic units [12] in this area are (Figure 2) the following: (i) sedimentary cover, particularly beach and dune sands, alluvia, sandy silts, and clays; (ii) metasedimentary rocks, namely micaschists, metagraywackes, and parageneisses; and (iii) granitic rocks, mainly two-mica granite, medium to coarse grained and biotitic granite, medium to fine grained.

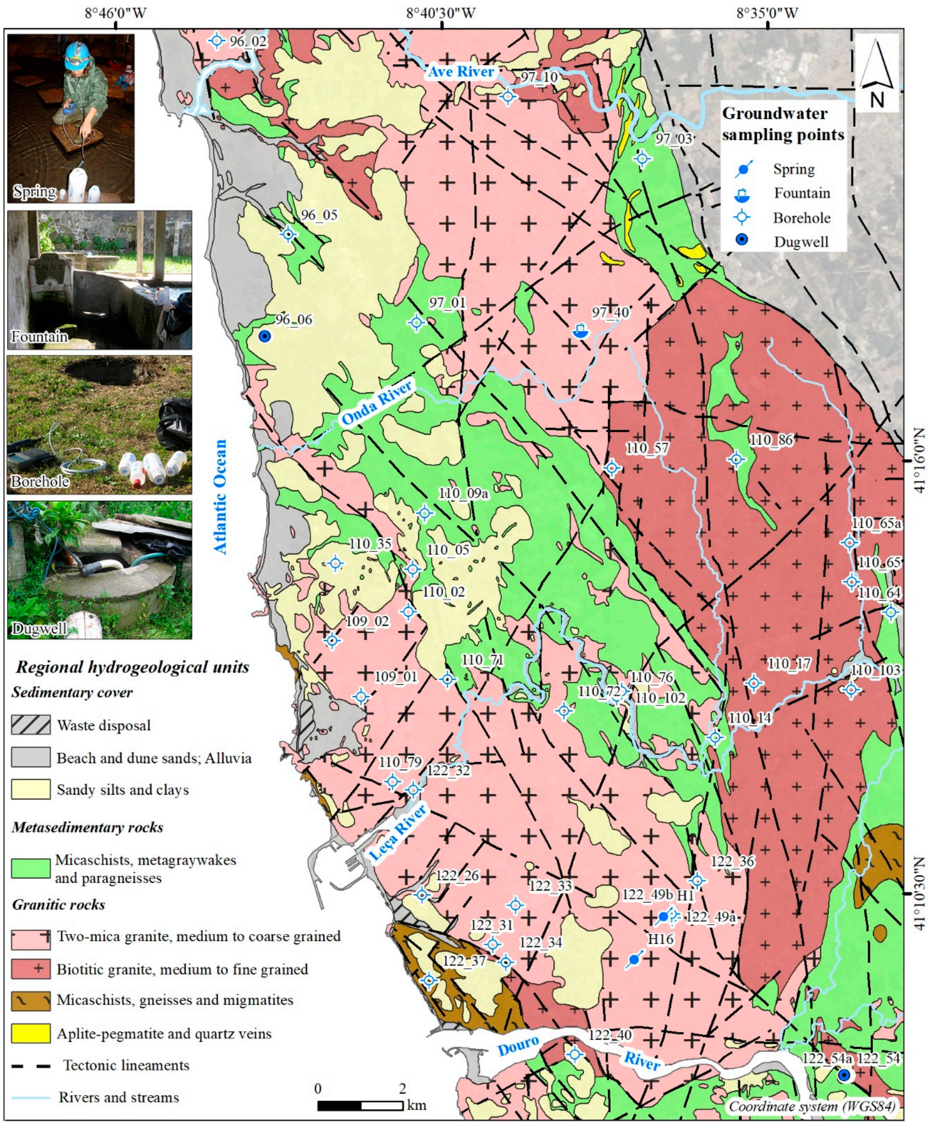


Figure 2. Regional hydrogeological setting of the Porto urban region (NW Portugal). Geological background updated from [63,65,69,70]. Hydrogeological framework adapted from [61,71,72]. Hydrogeological inventory and groundwater sampling points from [61].

3. Materials and Methods

The study area was assessed using various tools, as proposed by [67,68], namely geological and hydrogeological mapping, hydrogeochemical and isotopic techniques, and hydrodynamic characterization. Fieldwork campaigns were first carried out to identify major geologic features accountable for groundwater circulation pathways and to assess litho-structural heterogeneities. The field and laboratory data were evaluated in a GIS environment (ArcGis|ESRI, Redlands, CA, USA, and OCAD for Cartography Inc., Baar, Switzerland).

An urban hydrogeological field inventory was developed, which included more than 300 water points (springs, water mines, fountains, boreholes, and dug wells). Three fieldwork campaigns were carried out in May 2008, November 2008–January 2009, and May–June 2009. A total of 40 water points were selected for groundwater sampling and for chemical analyses consisting of 34 boreholes (mean depth of 117 m), 3 dug wells (mean depth of 11 m), 2 springs, and 1 fountain (connected to a water mine) (see Figure 2), most of them used for industrial and agricultural water supply. The inclusion of 2 dug wells and 2 springs in the fieldwork campaigns basically developed in the period 2005–2007 and were justified as follows: (i) to have dug wells represented in the hydrogeological unit "micaschists, metagraywackes and paragneisses"; (ii) to have springs represented (the 2 springs selected were two important springs of the historic Paranhos and Salgueiros water galleries in Porto City, which date back to the 16th Century).

Among the 40 samples, isotopic determinations of $\delta^{18}O$, $\delta^{2}H$, and ^{3}H were performed in 14 boreholes, 2 dugwells, and 2 springs in one fieldwork campaign. All the inventory and sampling sites were georeferenced with a high-accuracy GPS (Trimble® GeoExplorer, Sunnyvale, CA, USA). In situ measurements included water temperature (°C), pH, electrical conductivity (μScm^{-1}), dissolved oxygen ($mg\ L^{-1}$), and redox potential (mV) using a multiparametric portable equipment (Hanna Instruments, HI9828). The hydrogeochemical analyses included major and minor element concentrations and were acquired at the "Instituto Nacional de Saúde Doutor Ricardo Jorge" (Porto, Portugal). Environmental isotopes (^{18}O, ^{2}H, and ^{3}H) were measured at the "Instituto Tecnológico e Nuclear", meanwhile renamed "Campus Tecnológico e Nuclear/Instituto Superior Técnico (CTN/IST)" (Bobadela, Portugal). The $\delta^{18}O$ and $\delta^{2}H$ results were reported to the Vienna-Standard Mean Ocean Water (V-SMOW), and determinations were carried out using a mass spectrometer SIRA 10 VG-ISOGAS, applying the analytical methods described in [73,74], respectively. The tritium content was determined using the electrolytic enrichment and liquid scintillation counting method described by [75,76], using a PACKARD TRI-CARB 2000 CA/LL (see [77,78]). AquaChem 5.1 software was used for the hydrochemical interpretation.

The hydrodynamic interpretation of the groundwater systems was carried out based on pumping tests which were gathered from hydrogeological and geotechnical scientific and technical reports. Pumping data were analyzed using the Theis method, the Cooper–Jacob method, and the Theis recovery method [79–82], and the transmissivity and storage coefficient were evaluated. Moreover, the Logan approximation [83] was used to estimate transmissivity. The values of transmissivity, storage coefficient, and long-term well capacity were compiled from the hydrogeological reports and also contributed to the discussion.

The delineation of groundwater infiltration potential zones was assessed by the IPI-Urban index (details in [13,17–19]). The IPI-Urban is a weighted sum of the following eight factors, calculated using the analytical hierarchy process (AHP) [84]: land use, hydrogeological units, tectonic lineament density, drainage density, slope, and three other factors related to urban hydraulic and sanitation, sewer network density, stormwater network density and water supply network density.

4. Results and Discussion

4.1. Hydrogeochemical Approach

The physical and chemical parameters of groundwater samples collected during the fieldwork campaigns are summarized in the supplementary materials (Table S1). These groundwaters are slightly acidic with a median pH value of 6.2, and electrical conductivity (EC) values ranging from 95 to 1035 µS/cm, with a median value of 382 µS/cm, therefore, characterized as medium mineralized waters. These values are in good agreement with other data reported for this area [20,61,62]. The dissolved oxygen (DO) values in these groundwaters are in the range of 0.30–4.14 mg/L, with a median value of 1.75 mg/L. According to [85], these values are in accordance with those expected for most groundwaters (DO concentrations <5 mg/L, frequently <2 mg/L). The redox potential (Eh) measurements revealed that most of the studied groundwaters were in the range +0.1–+0.3 V, with a median of +0.15 V, which were values characteristic of most groundwaters [86] and within the water stability domain.

The major anions analyzed included bicarbonate (HCO_3^-), sulphate (SO_4^{2-}), chloride (Cl^-), and nitrate (NO_3^-). The groundwaters showed the following global rating in terms of median concentrations (mg/L): HCO_3^- (45.0) > Cl^- (41.2) > NO_3^- (40.0) > SO_4^{2-} (35.9). HCO_3^- has the highest standard deviation, while SO_4^{2-} has the lowest, and 31% of the water samples have concentrations of NO_3^- > 50 mg/L. Considering the European guidelines for the use of groundwater for human consumption and the Portuguese legislation for irrigation activities [87], nearly one-third of these water samples exceed the parametric value for nitrate (50 mg/L). This trend corroborates the results presented by [20,61,62]. Moreover, [20] classified a peri-urban area of Vila do Conde, between Ave and Onda rivers, with a potential high to moderate risk of nitrate contamination, based on the SINTACS and IPNOA indexes.

The major cations studied were sodium (Na^+), calcium (Ca^{2+}), potassium (K^+), and magnesium (Mg^{2+}), and the global rating was the following in terms of median concentrations (mg/L): Na^+ (37.0) > Ca^{2+} (13.0) > Mg^{2+} (7.9) > K^+ (4.0). The highest and the lowest standard deviation belong to Na^+ and Mg^{2+}, respectively. Among the other cations, most of the samples have concentrations of aluminium (Al^{3+}) and iron (Fe^{2+}) below 50 µg/L and concentrations of ammonia (NH_4) below 0.1 mg/L. Concerning the environmental isotopic approach, the median values for $\delta^{18}O$, δ^2H, and ^3H are, respectively, −4.42‰, −26.5‰ and 1.0 TU.

Considering the major anions and cations, we conclude that the hydrogeochemical signatures of these groundwaters are predominantly Cl-Na to Cl-SO_4-Na, however, the following facies may occur, Cl-SO_4-Na-Mg, Cl-SO_4-Na-Ca, and Cl-SO_4-Mg-Na (Figure 3a). Nevertheless, in the three fieldwork campaigns, five groundwater samples from boreholes drilled in diverse geological environments revealed a distinct hydrogeochemical facies in the bicarbonate domain: 110_17, HCO_3-Ca (biotitic granite, medium to fine grained); 110_64, HCO_3-Na to HCO_3-Na-Mg (mica schists, metagraywackes, and paragneisses); 110_65, HCO_3-Na (biotitic granite, medium to fine grained); 122_32, HCO_3-Na-Ca (two-mica granite, medium to coarse grained); 122_34, HCO_3-Ca-Mg (two-mica granite, medium to coarse grained). Moreover, two other borehole groundwater samples had HCO_3-Cl-Na facies, i.e., 110_02 (geological contact between two-mica granite, medium to coarse grained and gneisses) and 110_05 (geological contact between two-mica granite, medium to coarse grained and migmatites). [11,60–62,71,88] achieved similar hydrogeochemical signatures for the same hydrogeological units.

In order to better understand the hydrochemical signatures of these waters and the main processes controlling water mineralization, several correlations were established. Figure 3b–d indicates the following:

1. The strongest linear correlations were obtained in the water samples belonging to the shallow groundwater systems, represented by dug wells, fountains and springs.
2. Cl and Mg seem to have the same source for the shallow and deep groundwater systems, while the relation Cl and Na seems to point to a unique source only for the shallow systems;

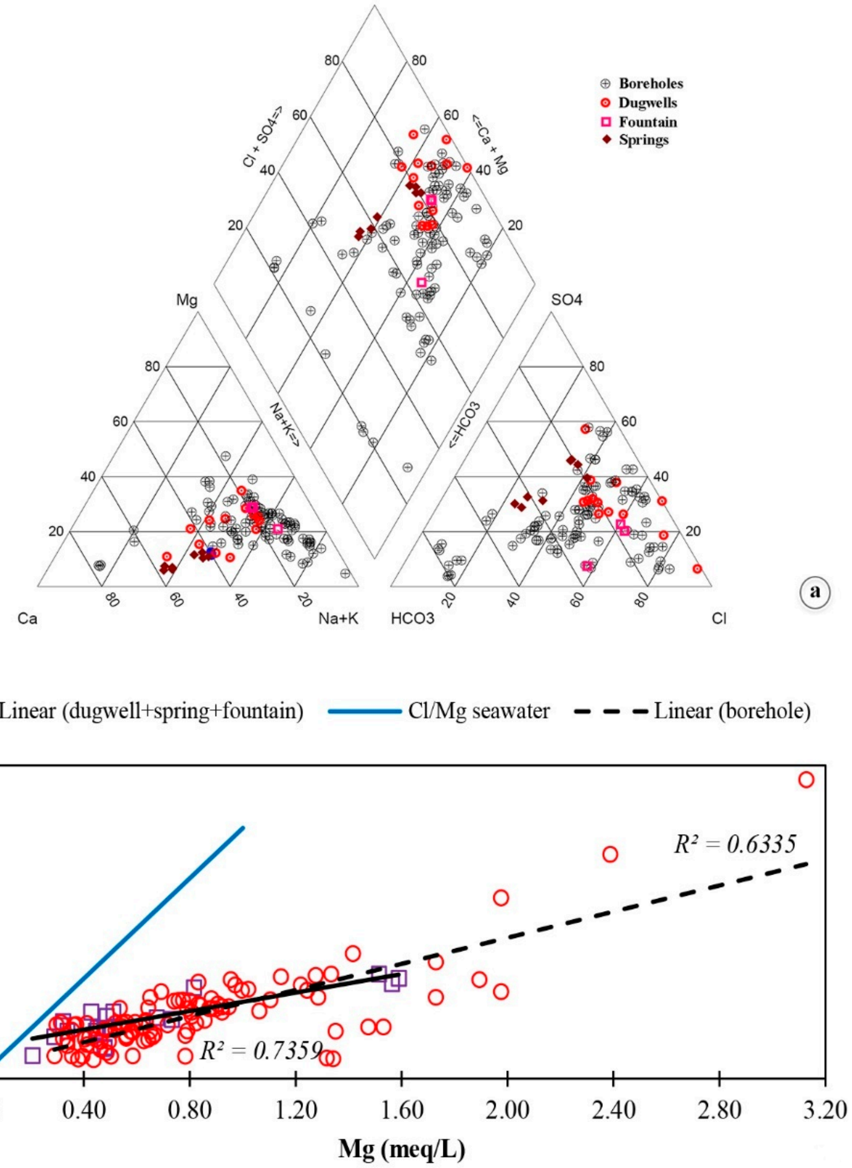
however, the common source of Cl and Mg is not marine, and the sea spray seems to be partially responsible for the Cl and Na; moreover, the proximity of several data to the Mg/Na seawater line outlines a partially common marine origin for these parameters.

3. The isotopic signatures of the groundwaters characterize a meteoric origin, since most of the water samples are positioned very close to the Global Meteoric Water Line (GMWL), defined by [89] and later improved by [90–92], and similar to the isotopic composition of the precipitation water samples, from the Portuguese Isotopes in Precipitation Network [93]. From the isotopic point of view, the following two main groundwater clusters have been identified: Group I stands for groundwaters collected from dug wells and boreholes, which presents a more enriched isotopic composition, similar to the Porto precipitation [93], corresponding to normal deviations related with seasonal variations of $\delta^{18}O$ and $\delta^{2}H$ on precipitation; Group II is composed of the spring samples and presents more depleted $\delta^{18}O$ and $\delta^{2}H$ values, which may be attributed to the fact that they could be ascribed to random precipitation events, resulting into a direct infiltration of meteoric waters along the fractured granitic rocks;
4. The meteoric origin of the shallow groundwaters seems to be reinforced by the SO_4-Ca facies, concerning the relationship with the precipitation data; therefore, the partial origin of SO_4 should be atmospheric pollution, enriched in SO_2 gases.
5. The common source of Cl and Mg must be anthropogenic, related to organic fertilizers, including sewage and livestock residues (liquid and semiliquid manure), and animal waste (e.g., bovines), in areas with a higher agricultural and/or livestock production activity, especially in the Vila do Conde, Trofa, and Northern Maia municipalities. Moreover, the good relationship between NO_3 and Cl for the shallow groundwater systems shows their partially common source; in fact, NO_3 is also an important constituent of fertilizers, either organic or synthetic, sewage, and animal and human wastes (e.g., [94]). The studied groundwaters do not present such a trend, indicating different sources for Cl and NO_3. Several studies developed in this region have reached similar conclusions (e.g., [20,62,95–97]).
6. The relations among Cl and Mg, and Cl and NO_3, may be ascribed to the urban and industrial sectors, particularly in the Porto, Matosinhos, and Vila Nova de Gaia municipalities, due to numerous groundwater potential contamination activities and their high density in some areas (cf. [17] for Porto and Vila Nova de Gaia urban areas), i.e., wastewater leakages, cesspools, and solid waste tanks contamination, hydrocarbons present from vehicle fuels and industrial processes, such as solvents and degreasing agents, namely trichloroethylene, which is one of the most common.
7. HCO_3 and Ca have a reasonable correlation among the borehole water samples, and the correlation between HCO_3 + NO_3 and Na + Ca is good for the same water samples. This trend seems to indicate that these parameters have partially the same origin that probably should be ascribed to water–rock interaction, namely the hydrolysis of plagioclases presented in granitic rocks.

Therefore, the mineralization of these groundwaters seems to be controlled by the following three main sources/processes: (i) meteoric, including sea spray, contributing with the Cl^- and Na^+ ions, and atmospheric pollution, particularly responsible by the presence of $SO_4{}^{2-}$; (ii) anthropogenic contamination, particularly introducing Cl^-, Mg^{2+}, and $NO_3{}^-$; and (iii) water–rock interaction, adding $HCO_3{}^-$, Na^+, and Ca^{2+}.

Since the altitude differential of the springs sampling sites is rather small, in the study region, (spring waters are the most representative of local precipitation), it was difficult to estimate the altitude of recharge areas ascribed to the groundwaters from boreholes (usually recharged far from the discharge). In fact, the correlation between the altitude of the spring sites and $\delta^{18}O$ values was very low ($r = -0.14$).

Tritium concentrations, in the range 0.0–4.6 TU, are consistent with the precipitation ^{3}H record measured at the Porto meteorological station, with a weight annual mean of 4.5 TU (see [100]). Therefore, for coastal areas, according to [49], the ^{3}H values related to the studied groundwaters could correspond to a mixture of recent waters, with short and fast underground flow paths (<5–10 years) and relatively close to the surface, and submodern waters where recharge took place before the thermonuclear events in 1952.



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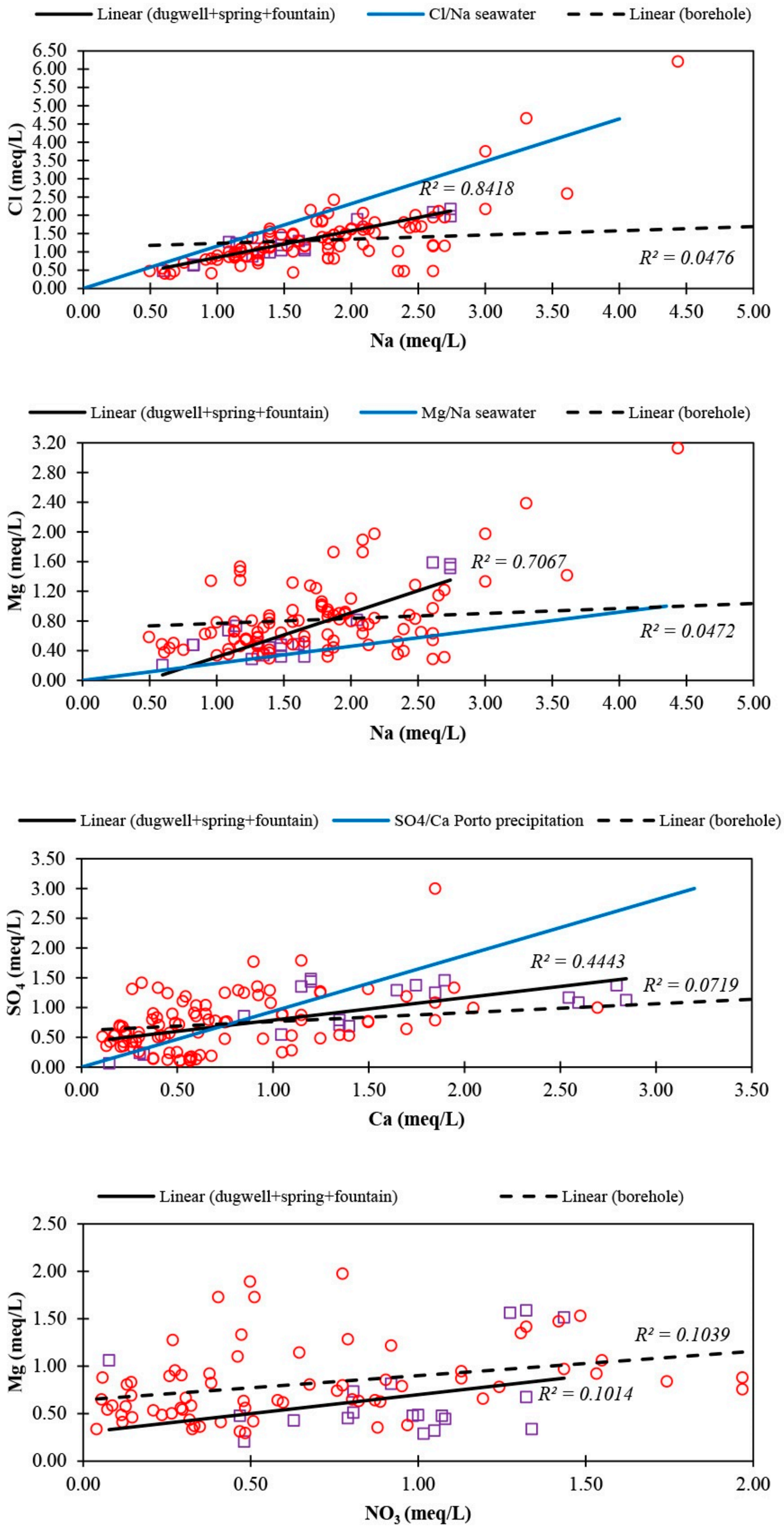

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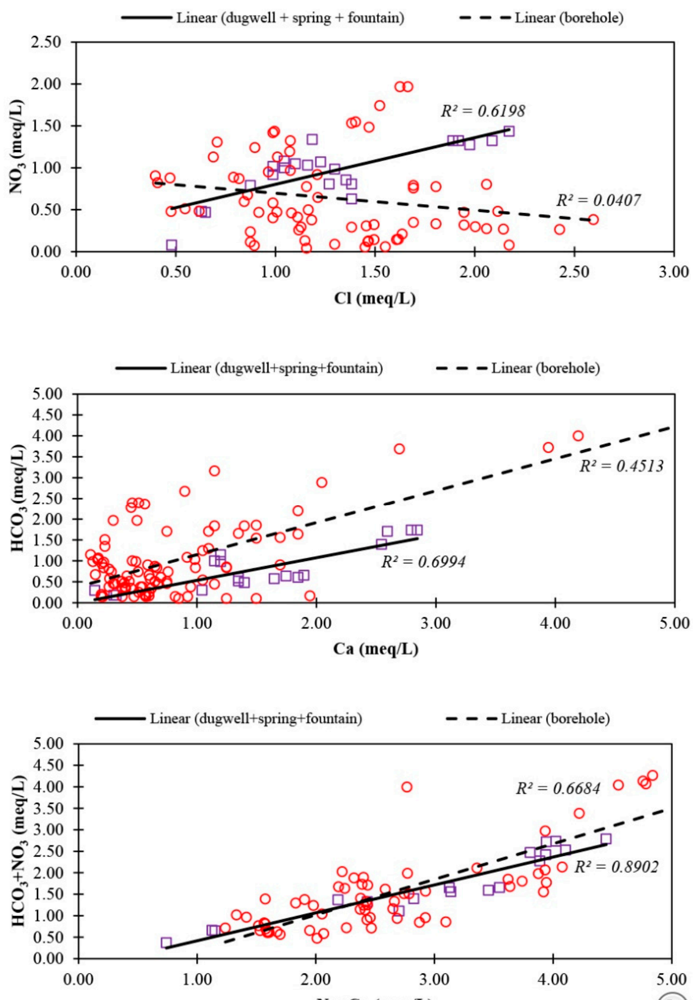
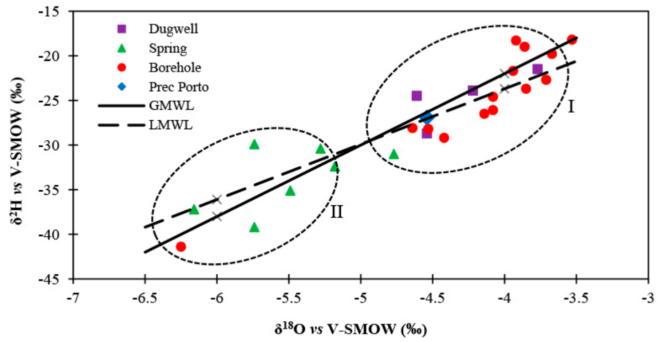


b

Average chemical composition (meq/L) for Porto precipitation (adapted from [98, 99])						
HCO_3	Cl	SO_4	Na	K	Ca	Mg
0.046	0.268	0.085	0.244	0.008	0.09	0.058

c



d

Figure 3. Hydrochemical and isotopic relationships for groundwater samples collected during the three fieldwork campaigns. (**a**) Piper diagram; (**b**) Scatter diagrams for several hydrochemical parameters, R-squared value (R^2) is indicated for each studied linear relationship, and seawater relations are those reported by [85]; (**c**) The average chemical composition of Porto precipitation, reported by [98] and [99]; (**d**) $\delta^{18}O$ vs. δ^2H signatures of the studied groundwater samples. The global meteoric water line (GMWL) ($\delta^2H = 8\delta^{18}O + 10$, [89]), the local (Porto meteorological station) meteoric water line (LMWL) ($\delta^2H = (6.20 \pm 0.33)$ and $\delta^{18}O + (1.12 \pm 1.16)$, r = 0.93, [93]), and the long-term mean isotopic composition of Porto precipitation (Prec. Porto) ($\delta^2H = -26.9‰$ and $\delta^{18}O = 4.54$ [93]) were plotted as reference.

4.2. Hydrodynamical Assessment

For this evaluation, the study area was divided into the following two key sectors (Figure 4a), each sector dominated by a hydrogeological unit: (i) Sector 1, in the geological contact of two-mica granite, medium to coarse grained and metasedimentary rocks, and also in the biotitic granite, medium to fine grained, with 16 boreholes; (ii) Sector 2, in the two-mica granite, medium to coarse grained, with 18 boreholes and five piezometers.

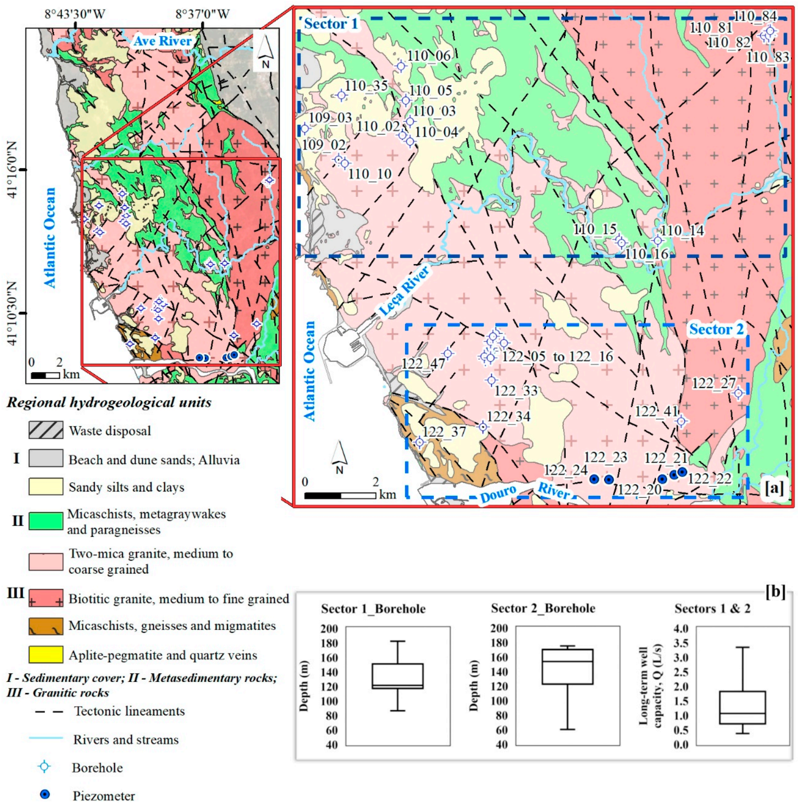


Figure 4. Inventory of boreholes and piezometers used for the hydrodynamical assessment. (**a**) Study sites (Sectors 1 and 2) are shown on the right side of the figure; (**b**) Depth of boreholes and long-term well capacity for Sectors 1 and 2.

The median depth of the boreholes is 121 m in Sector 1, and higher in Sector 2, around 154 m (Figure 4b). For piezometers, the depth range is 15–34 m. The median value for the thickness of the weathering profile is null for both sectors, and it varies in the following ranges: 0.0–17.0 m in Sector 1, and 0.0–26 m in Sector 2. Concerning long-term well capacity, the minima, maxima, and median values are very similar in both sectors, i.e., 0.4 L/s, 3.5 L/s, and 1.1 L/s, respectively (Figure 4b). There was no correlation found between depth of boreholes and long-term well capacity, or between depth of screens and long-term well capacity.

For the assessment of transmissivity and storage coefficient values, we selected two boreholes and one piezometer, i.e., boreholes 110_02 and 122_09 in Sectors 1 and 2, respectively, and piezometer 122_23 in Sector 2 (Figure 5). Concerning borehole 110_02, the transmissivity values obtained during the pumping period were 21.8 m^2/day and 34.4 m^2/day, for the borehole and the observation well 110_03, respectively, while, for the recovery period, it was 24.3 m^2/day. Additionally, the storage coefficient value was 3.1×10^{-4}. Regarding borehole 122_09, the transmissivity values obtained during the pumping period were 2.8 m^2/day and 6.7 m^2/day for the borehole and the observation well 122_07, respectively, while, for the recovery period, it was 2.1 m^2/day. Moreover, the storage coefficient value was 2.5×10^{-5}. For piezometer 122_23, the transmissivity values obtained during the pumping period were 51.3 m²/day and 55 m²/day. Furthermore, the storage coefficient values were 3.1×10^{-2} and 3.9×10^{-3}.

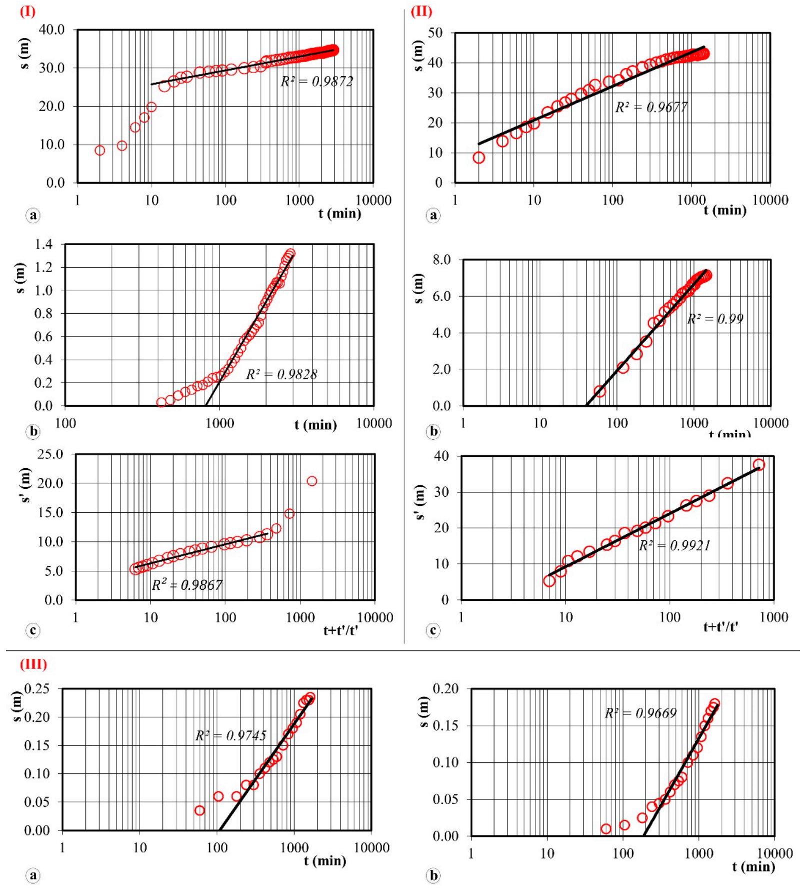


Figure 5. Interpretation of pumping tests. (**I**) 110_02, Cooper–Jacob method: (**a**) Pumping period data for 110_02; (**b**) Pumping period data for the observation well 110_03, located 370 m from 110_02; (**c**) Theis recovery method; (**II**) 122_09, Cooper–Jacob method: (**a**) Pumping period data for 122_09; (**b**) Pumping period data for the observation well 122_07, located 128 m from 122_09; (**c**) Theis recovery method. (**III**) 122_23, Cooper–Jacob method for two observation wells: (**a**) Located 16 m (**b**) Located 63 m.

Due to the lack of well-documented aquifer conditions and complete pumping tests, a Logan approximation was achieved using specific capacity values for 69% of the boreholes in two sectors (Figure 6). According to [101], the Logan method can give a reasonable first estimate of transmissivity, provided that near equilibrium conditions are achieved when the maximum drawdown is measured. Therefore, Figure 6a shows good correlations among the Logan method and the other methods, particularly the Theis and the Cooper–Jacob methods. Additionally, transmissivity values are quite variable in both sectors, in the range of 0.1–26 m²/day. Nevertheless, the median values of transmissivity are very similar for the different methods and even for the two sectors, 1.8–4.0 m²/day (Sector 1) and 2.5–4.2 m²/day (Sector 2), (Figure 6b).

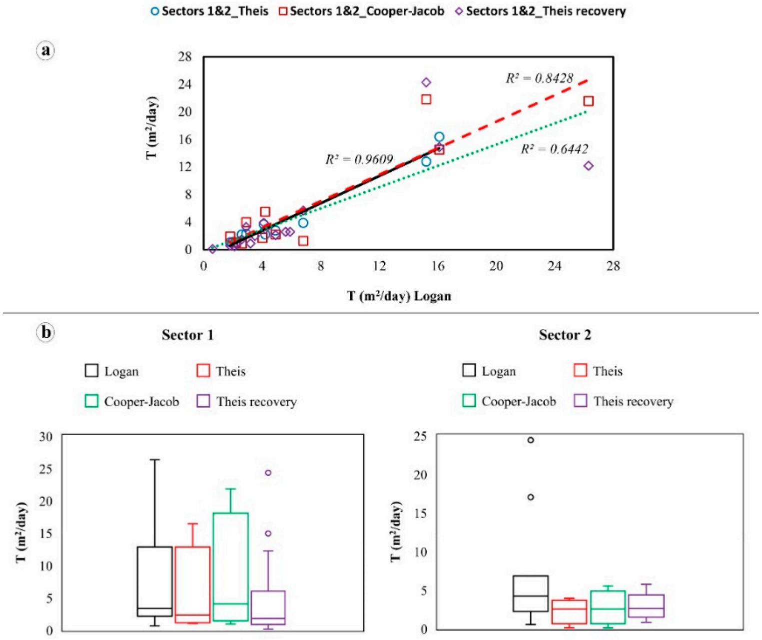


Figure 6. Transmissivity values for Sectors 1 and 2. (**a**) Logan vs. other methods; (**b**) Box-and-whisker diagrams for Sectors 1 and 2.

Considering the storage coefficient, values are also variable, in the range of 2.5×10^{-5}–4×10^{-2}, which characterizes confined to semi-confined groundwater conditions.

Very good correlations ($R^2 > 0.85$) were found between long-term well capacities and transmissivities in both sectors. The highest values of long-term well capacity and transmissivity could be explained by the local presence of a very productive fracture, or to a direct connection with a nearby surface water body or a porous overlying aquifer.

All these conclusions confirm other investigations, performed by several authors, in fractured-rock aquifers in the Porto region and Portugal (e.g., [60,61,72,102,103] and references therein).

The hydrodynamic behavior of these aquifer systems meets the criteria mentioned in the literature for fractured-rock aquifers over the last four decades (e.g., [104–113]).

4.3. Urban Infiltration Potential Index (IPI-Urban)

The spatial distribution and explanation of six thematic layers (Figure 7) involved in the computation of the IPI-Urban (Figure 8), i.e., tectonic lineaments density, slope, drainage density, sewage network density, stormwater network density, and water supply system density are presented in this section.

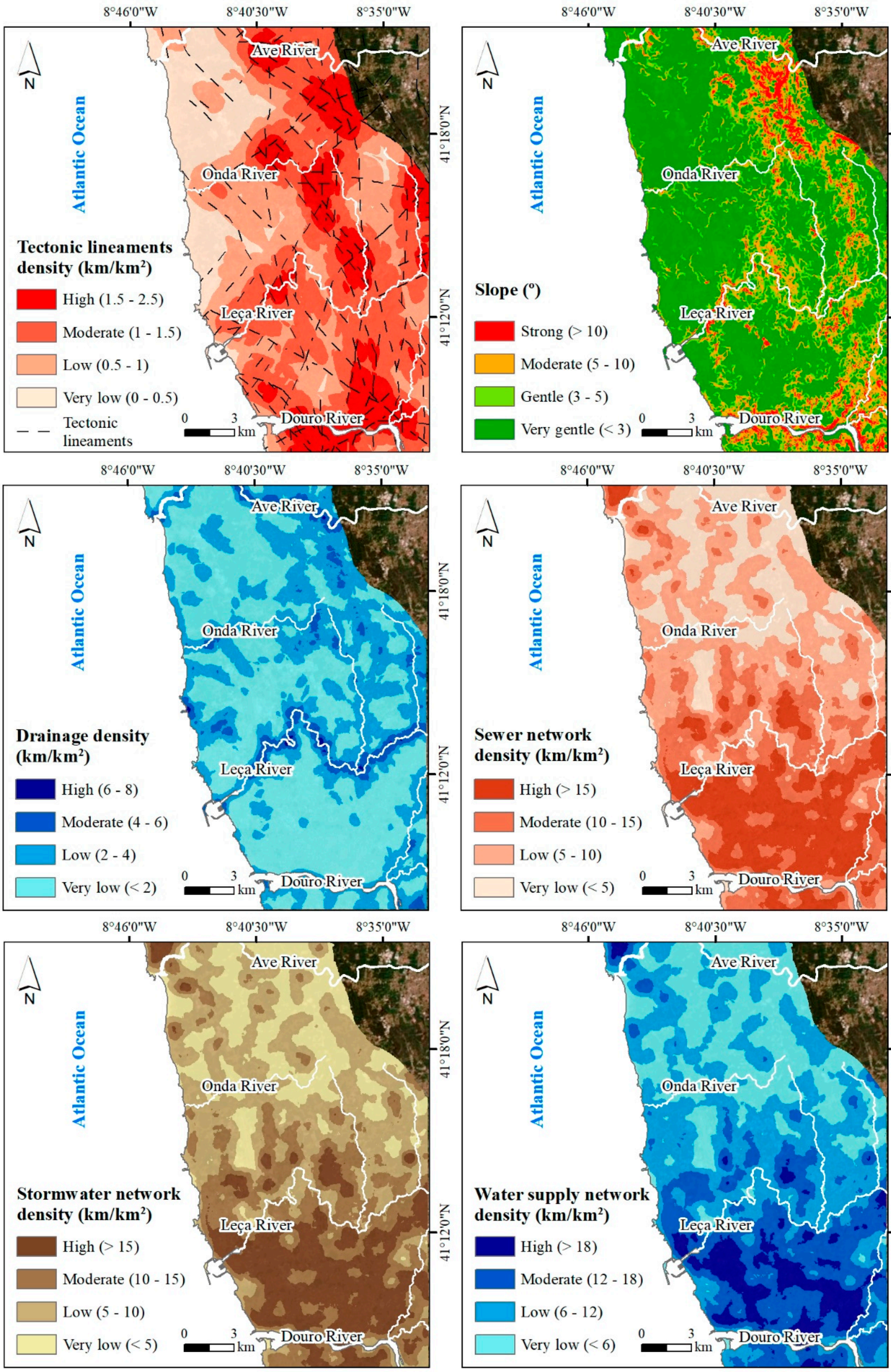


Figure 7. Tectonic lineaments density, slope, drainage density, sewage network density, stormwater network density, and water supply system density in the Porto urban region (NW Portugal).

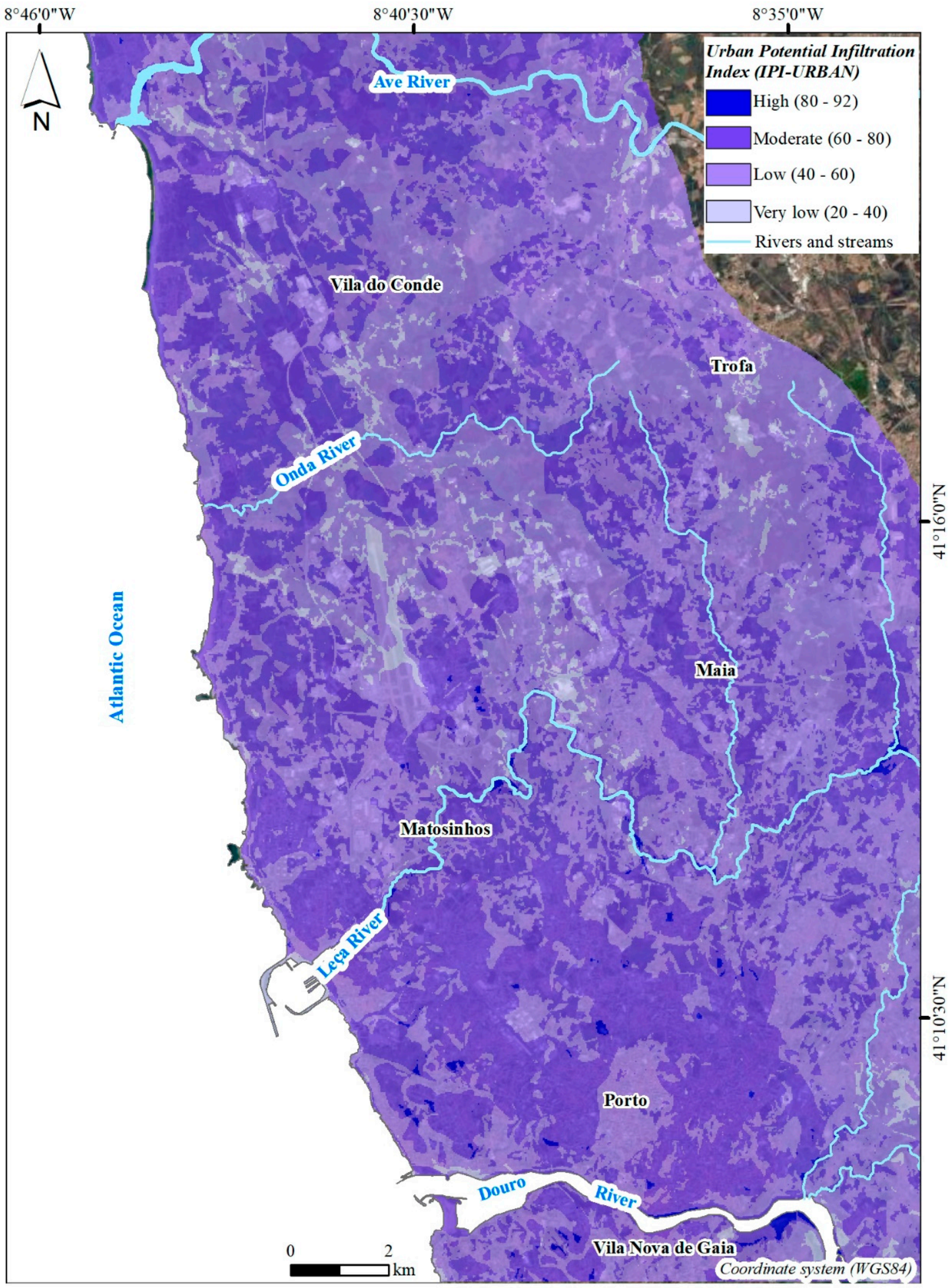


Figure 8. Urban infiltration potential index (IPI-Urban) in the Porto urban region (NW Portugal).

Land use and hydrogeological units' thematic layers were previously introduced in Section 2. Nevertheless, briefly, land use plays a crucial role in this region, and the following two classes dominate: urban and industrial areas (ca. 41%), and agricultural and forest areas (ca. 52%). This suggests that surfaces of low to very low permeability cover more than one-third of the region and must be responsible for the reduction in infiltration and, consequently, direct groundwater recharge. Hydrogeological units also play a key role in groundwater occurrence. Granitic rocks are the most representative lithology, namely the two-mica and biotitic granites (ca. 56%).

Concerning tectonic lineaments, most of the region (ca. 65%) has moderate to low densities (0.5–1.5 km/km^2). The highest densities (>1.5 km/km^2, ca. 20%) occur disseminated in the region, and the lowest densities (<0.5 km/km^2, ca. 15%) are mostly concentrated in the west-northwestern (W-NW) area, where the sedimentary cover has its most representative domain.

As for slope, much of the region (ca. 81%) has very gentle to gentle gradients (<5°). Moderate and strong gradients (>5°) arise in almost 19% of the region and are mostly connected with the Ave, Leça and Douro river valleys.

The region has mostly (ca. 92%) a very low to low drainage density (<4 km/km^2). The highest densities (4–8 km/km^2) are closely related with the four major rivers and streams (Ave, Onda, Leça, and Douro rivers).

Regarding sewer and stormwater networks, the largest part of the region (ca. 58%) has low to moderate densities (5–15 km/km^2). The highest densities (>15 km/km^2) are concentrated (ca. 21%) in the most representative municipalities, namely Porto and Matosinhos.

Ultimately, the dominant water supply system classes (ca. 66%) are low to very Low (<12 km/km^2). Most of the remaining parts of the region (ca. 25%) has moderate densities (12–18 km/km^2) which are concentrated in Porto, Matosinhos, and Maia municipalities.

Regarding the IPI-Urban index, the overall scenario shows that in 96% of the urban region, the dominant classes are low (ca. 54%) and moderate (ca. 42%). The low class seems to be mostly connected with the two-mica and biotitic granites in areas where these hydrogeological units coexist with an agricultural and forest cover. However, the moderate class appears to be associated firstly with the sedimentary cover. Moreover, this class occurs in areas covered by an urban and industrial fabric. Although this may seem incoherent, the higher densities of the urban hydraulic and sanitation features (sewer, stormwater, and water supply networks) are found in these areas. Therefore, on a regional scale, the major role of these features is to enhance the natural low infiltration potential. The very low class occurs in approximately 4% of the region and is linked to the "Micaschist, metagreywacke and paragneiss" and "Micaschist, gneiss and migmatite" hydrogeological units, especially where these units are covered by urban and industrial areas, as well as the airport and harbor areas. The high class represents less than 1% of the region and corresponds to very confined areas, mainly between the Leça and Douro rivers and to the south of the Douro river.

5. Hydrogeological Conceptual Ground Models

The building of a conceptual hydrogeological model is presented as the first step in the entire process of modeling Earth systems. A multicriteria methodology supported in an accurate GIS mapping allows a perspective from geosciences for the paradigm of smart cities, namely through multidisciplinary, interdisciplinary, and transdisciplinary approaches (e.g., [35,36]).

In the study of crystalline aquifers, hydrogeomorphology has a fundamental role in the refinement of conceptual hydrogeological models, which aim at the sustainability of groundwater resources [17,18]. In this kind of system, there are many factors, some of them very complex, that control the infiltration and circulation of groundwater at the local/regional scale.

Figure 9 shows the hydrogeological conceptual models for the Porto urban region (Figure 9I), and the Porto urban area (Figure 9II). This conceptualization included the identification of different kinds of aquifer systems in an urban and pre-urban scenario. The main criteria considered were the hydrogeological units features, the morphostructure, the land use, the hydrogeochemical, isotopic and hydrodynamical characteristics, the infiltration potential, and the recharge processes (Table 1).

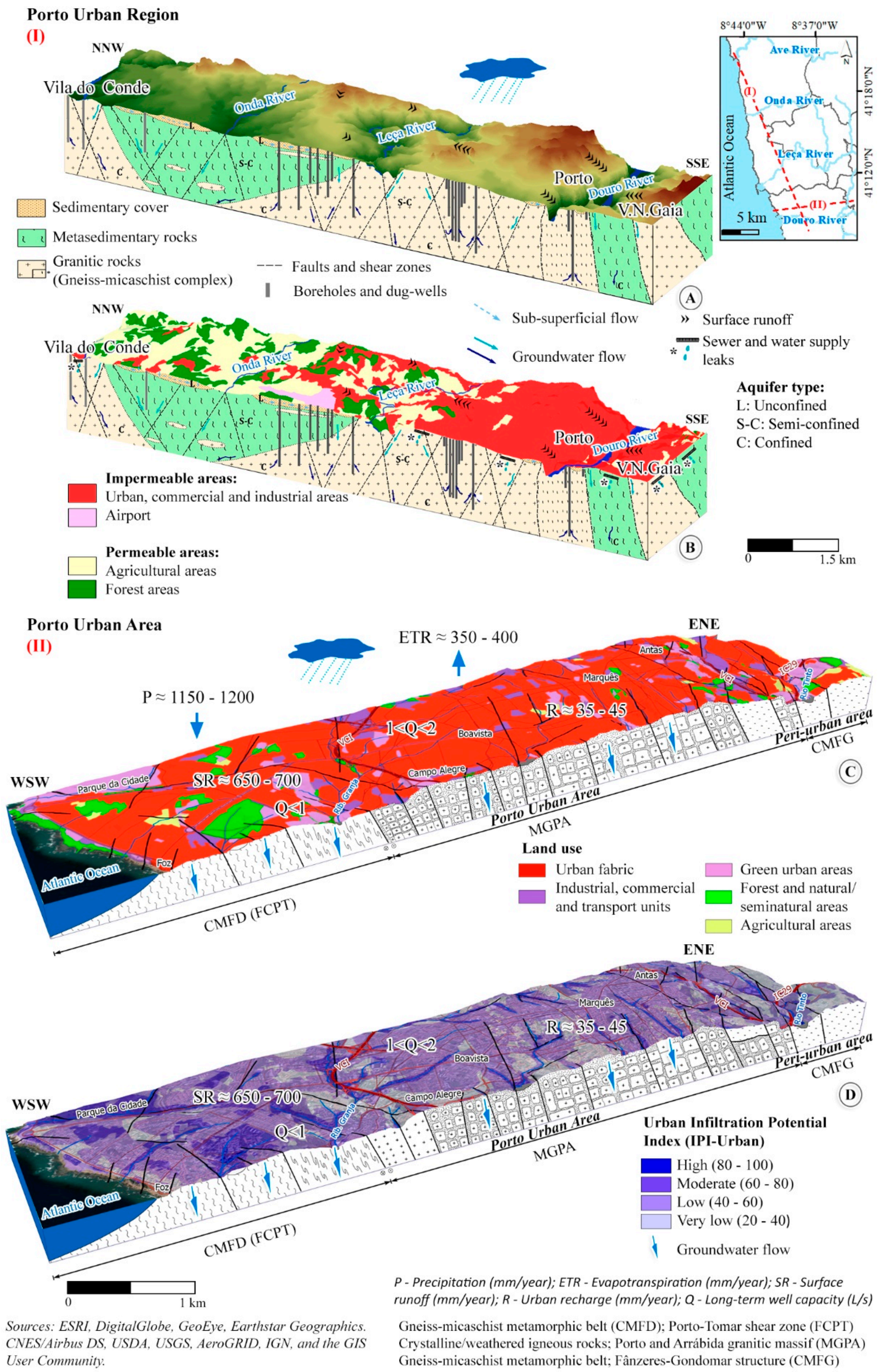


Figure 9. Urban hydrogeological conceptual models (revised and updated from [61,114]. (**I**) Porto urban region: (**A**) Pre-urban scenario; (**B**) Urban scenario). (**II**) Porto urban area: (**C**) Land use context; (**D**) IPI-Urban framework.

Table 1. Regional hydrogeological units (cf. Figure 2) and related features in the Porto urban region (summarized and updated from [17,18,20,61,62,71,72,103,115]).

Hydrogeological Groups				Sedimentary Cover		Metasedimentary Rocks	Granitic Rocks			
Regional Hydrogeological Units (RHU)				**Beach and Dune Sands; Alluvia**	**Sandy Silts and Clays**	**Micaschists, Metagraywackes and Paragneisses**	**Two-mica Granite, Medium to Coarse Grained**	**Biotitic Granite, Medium to Fine Grained**	**Micaschists, Gneisses and Migmatites**	**Aplite-pegmatite and Quartz Veins**
HYDROGEOLOGICAL FEATURES	**Thickness (m)**			<12	10–20	not applicable				
	Weathering profile	low (m)		not applicable		10–20			5–10	<5
		high (m)					20–40	20–40		
		silty and/or clayey				X		X	X	X
		sandy					X	X	X	X
	Connectivity to the drainage system	with		X	X					
		possible				X	X	X	X	X
	Type of media flow	porous		X	X					
		fissured				X	X	X	X	X
	Hydrochemical facies			Cl-Na to NO_3-Na		Cl-Na to Cl-SO_4-Na				
	Environmental isotopes	$\delta^{18}O$ (‰)		not determined		−6.5 to −3.5				not determined
		$\delta^{2}H$ (‰)				−40 to −20				
		^{3}H (TU)				< 5				not determined
	Hydrodynamic parameters	long-term well capacity, Q (L/s)	very low ($Q \leq 1$)		X	X	X	X	X	
			Low ($1 < Q < 2$)	X						X
		Transmissivity (T, m^2/day)		15–20	< 1	1–3	0.5–2		1–3	
		Storage coefficient (S)		10^{-1}–10^{-2}	10^{-2}–10^{-3}	10^{-3}–10^{-5}				
	Aquifer confinement			unconfined	aquitard	semi-confined to confined				
	More suitable exploitation structures	dug-wells, galleries, and springs		X	X					X
		boreholes				X	X	X	X	X
	Direct groundwater recharge (%)			25–30	20–25	10–15	5–10			15–20
	Urban infiltration potential index (IPI-Urban)	high		X						
		moderate		X	X		X	X		
		low			X	X	X	X	X	X
		very low				X			X	

Regarding the Porto urban region, the following two perspectives are presented: a pre-urban context (Figure 9IA) and an urban context, with the main levels of land use (Figure 9IB), which is relevant to evaluate the impact on infiltration and direct recharge of these aquifer systems. For the Porto urban area, two viewpoints are shown, i.e., the main land use classes (Figure 9IIC) and the main IPI-Urban classes (Figure 9IID). For both views, several hydroclimatic and hydrodynamical parameters were added.

The analysis of both models allowed us to characterize the following three aquifer systems, i.e., superficial, intermediate, and deep, which are interconnected, sometimes in a discontinuous manner:

a. A superficial unit corresponds essentially to the sedimentary cover and the weathered/fractured zones of metasedimentary and granitic rocks that constitute a porous medium with hydraulic connection to the drainage system. The water table is close to the surface (<5 m). The more suitable exploitation structures are dug wells and springs associated, or not, to galleries, and the long-term well capacities are low (1 < Q < 2 L/s). Sedimentary cover can reach thicknesses of almost 30 m. In crystalline rocks, the weathering thickness is variable, and can reach values of 20–40 m locally (e.g., [116]), affecting transmissivity, which is generally low (<5 m^2/day), and storage coefficient. The sedimentary cover constitutes an unconfined aquifer, while, in crystalline rocks, it corresponds to a semi-confined one. The hydrochemical facies is mostly Cl-Na. The infiltration potential is moderate to high and the groundwater recharge is direct, through infiltration of precipitation.
b. Intermediate aquifers constitute a fractured media, which may have a hydraulic connection to the drainage system. The more suitable exploitation structures are boreholes and the long-term well capacities are mostly very low (Q < 1 L/s). Transmissivity values are low (<5 m^2/day) and these aquifers are semi-confined to confined. Groundwater has a short and shallow circuit with a Cl-Na to Cl-SO4-Na hydrochemical facies. The infiltration potential is moderate to low and the groundwater recharge occurs by leakage of the overlain levels or directly from the surface, namely by geological structures (e.g., geological contacts, faults, and veins), with favorable geo-hydraulic characteristics for the groundwater flow (e.g., major deep, open and not filled fractures, and intersections between tectonic lineaments).
c. Deep aquifers correspond to unweathered and massive crystalline bedrock, with closed fractures. They constitute a fissured media, where groundwater flow tends to have a weak regime with very low transmissivities and the hydraulic characteristics are confined.

6. Conclusions

Expanding our understanding of the behavior of fractured bedrock systems in urban environments will continue to be a research challenge requiring multidisciplinary approaches such as the one presented in this work.

The Porto urban region is the second largest metropolitan area in Portugal mainland, with a high population density, living in a land covered by urban and industrial areas (ca. 41%), mostly in the south part of the region, and agricultural and forest areas (ca. 52%), in the north.

The climatic conditions, the morphotectonic and geological background, mainly comprised of crystalline formations, namely granites and metasedimentary rocks, are responsible for the groundwater resources availability.

These groundwaters have median values for pH, electrical conductivity, dissolved oxygen, and redox potential of 6.2, 382 µS/cm, 1.75 mg/L, and +0.15 V, respectively. Considering major anions, the median concentrations for bicarbonate, sulphate, chloride, and nitrate are 45.0 mg/L, 35.9 mg/L, 41.2 mg/L, and 40.0 mg/L, respectively. In addition, for the major cations the median concentrations for sodium, calcium, potassium, and magnesium are 37.0 mg/L, 13.0 mg/L, 4.0 mg/L, and 7.9 mg/L, respectively. The hydrogeochemical facies are mainly Cl-Na to Cl-SO_4-Na. Moreover, the median values for $\delta^{18}O$, δ^2H, and ^3H are −4.42‰, −26.5‰, and 1.0 TU, respectively. All these characteristics are mostly dependent on the proximity of the Porto urban region to the Atlantic Ocean, the anthropogenic and agricultural contamination processes, and, with a lesser impact, the water–rock interaction, since groundwater has fast, shallow flow paths, and short residence times.

This fractured environment is the key to several hydrodynamic characteristics, which characterize confined to semi-confined groundwater conditions, namely low to very low long-term well capacities, with a median value of 1 L/s; low transmissivities, with median values in the range 2–4 m^2/day; and, generally, low storage coefficients, in the range 10^{-5}–10^{-2}.

The infiltration potential and the groundwater recharge are typically low in this fissured background. This low potential largely arises in zones where granitic rocks and agricultural/forest areas coexist. However, a moderate infiltration potential also occurs, naturally associated with the sedimentary cover, and artificially to the urban hydraulic and sanitation features.

The main conclusions summarized above contribute to outline recommendations for policymakers for the environmental protection, reasoning on the planning with nature and to the sustainable water resources management for the urban areas. In fact, integrated groundwater resources management is vital to evaluate water use, water availability, and to design balanced solutions in a changing society, environment, and climate.

Last but not least, in the current context of climate change, water shortage and groundwater depletion, along with a pandemic scenario, the authors support this impressive message by [117], "There is a need for the incorporation of groundwater in national IWRM plans and promotion of groundwater resource management in the programs of river basin agencies. Planned conjunctive management of groundwater and surface-water resources in many cases represents the best prospect for improving water-supply security for urban and irrigation use, and for sustainable resources."

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4441/12/10/2797/s1, Table S1: Physical, chemical, and isotopic parameters for groundwater samples collected during the fieldwork campaigns.

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