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Article

A 3D Geodatabase for Urban Underground Infrastructures: Implementation and Application to Groundwater Management in Milan Metropolitan Area

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Abstract: The recent rapid increase in urbanization has led to the inclusion of underground spaces in urban planning policies. Among the main subsurface resources, a strong interaction between underground infrastructures and groundwater has emerged in many urban areas in the last few decades. Thus, listing the underground infrastructures is necessary to structure an urban conceptual model for groundwater management needs. Starting from a municipal cartography (Open Data), thus making the procedure replicable, a GIS methodology was proposed to gather all the underground infrastructures into an updatable 3D geodatabase (GDB) for the metropolitan city of Milan (Northern Italy). The underground volumes occupied by three categories of infrastructures were included in the GDB: (a) private car parks, (b) public car parks and (c) subway lines and stations. The application of the GDB allowed estimating the volumes lying below groundwater table in four periods, detected as groundwater minimums or maximums from the piezometric trend reconstructions. Due to groundwater rising or local hydrogeological conditions, the shallowest, non-waterproofed underground infrastructures were flooded in some periods considered. This was evaluated in a specific pilot area and qualitatively confirmed by local press and photographic documentation reviews. The methodology emerged as efficient for urban planning, particularly for urban conceptual models and groundwater management plans definition.

Keywords: Milan; underground structures and infrastructures; 3D geodatabase; geographic information systems; urban underground; groundwater management; groundwater modelling; Topographic Database

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1. Introduction

Cities are intricate areas, where different elements interact. In the past, their expansion has generally occurred in the horizontal direction (urban sprawl) [1–3]; despite this, underground urbanism was already conceived [4–8]. According to previsions, 70% of the world's population is expected to live in cities by 2050 [9]. As a consequence of this rapid urbanization, space hunting is moving towards a three-dimensional trend [10,11]: vertical urban development has thus been adopted to counteract urban sprawl [1], thus increasing population density. This urban densification is leading to the building of deeper structures [12,13], which increases the tendency to "go underground" [14–18].

The increasing need for space in urban areas has recently enhanced urban underground consideration [8,12,19]. Four subsurface resources are key to pursuing sustainable urban underground development: space for constructions, materials, water and energy [10,19–21].

These resources interact with each other [22]. In particular, a strong interaction between groundwater and underground infrastructures has been observed [21,23,24]. In the last few decades, many cities around the world have faced a rising trend in groundwater levels, caused by the deindustrialization process. This produced some interferences between groundwater and underground infrastructures, such as subways, car parks and basements [25–32]. The implementation of a geodatabase (GDB), including 3D locations and uses of the underground structures, could help to manage this issue [22]. In this way, part of the large amount of data generally available in urban areas [33], but not stored in a systematic way [34], could be gathered in a unique structure. The GDB will contribute to process data to be used for groundwater management, thus enabling the definition of an urban conceptual model, a necessary step for 3D numerical groundwater flow modelling. For this reason, these data need to be integrated with geological, hydrological, geomorphological and other required information. Furthermore, the increasing interest in open data for urban management and groundwater issues is a topic to be considered [35,36]. Indeed, the opening of data entails several barriers, related both to providers (i.e., incomplete or obsolete information) and users (i.e., complexity of using and interpreting data); however, a large number of benefits are related to open-data: among them, the improvement of policy-making processes, the creation of new information combining existing data, and avoiding repetitively collecting the same information are included [37–39].

The city of Milan experienced a strong groundwater table rise in the last few decades [40]. As numerical groundwater flow modelling is the primary tool for evaluating the interactions between groundwater and underground infrastructures [34], different 3D models have been realized for the urban area of Milan [41–43]. Among the underground infrastructures listed above, all these numerical models focused only on the subway lines: interactions between groundwater and car parks were not evaluated.

The aim of this work is to propose a methodology to estimate, on an urban scale, the volume of underground infrastructures lying below the groundwater table. This is the basis for a further evaluation of the impacts of the interaction between groundwater and infrastructures, such as the perturbation of groundwater flow by infrastructures or the groundwater flooding of non-waterproofed infrastructures. Three categories of infrastructures were considered in this study: (a) private car parks, (b) public car parks and (c) subway lines/stations and underground railway. To the best of our knowledge, this is the first time that car parks were considered in evaluating groundwater/infrastructure interactions in the city of Milan. On the contrary, car parks have been considered in numerical models in other towns [44–46]. The last part of this work is devoted to the evaluation, within a pilot area, of the impact of groundwater (i.e., flooding) on non-waterproofed public car parks and subway lines and stations. The comparison between the results of this evaluation and actual flooding events, identified by local press reviews and photographic documentation reviews, helped to validate, qualitatively, the whole methodology. The methodology here proposed is developed for the case study of Milan—however, it could be applied to other cities worldwide with similar characteristics (i.e., municipalities characterized by a subsurface infrastructure development).

2. Study Area

The study area (Figure 1) covers 440 km^2 in the Milan metropolitan area, between longitudes 1,503,000 and 1,525,000 and latitudes 5,025,000 and 5,045,000 (Monte Mario Italy 1; ESPG: 3003). The city of Milan is inhabited by 1.4 million people [47] and has had strong industrial and agricultural development [48]. It is located in the Po Plain, which hosts a sedimentary aquifer system whose hydrogeological structure has been previously investigated in detail [49]. Three main hydro structures can be identified: a shallow hydro structure (ISS), an intermediate hydro structure (ISI) and a deep hydro structure (ISP). ISS and a portion of ISI are visible in Figure 2. ISS is mainly composed of gravels and sands and hosts a phreatic aquifer. In the study area, it has a medium thickness of 50 m and its bottom surface goes from 100 m a.s.l. (to the North) down to around 50 m a.s.l. (to the South). ISI hosts a semiconfined aquifer mainly composed of sand and gravels, with an increasing presence of silty and clayey layers compared to the upper hydro structure. Its bottom surface goes from 70 m a.s.l. (to the North) down to −50 m a.s.l. (to the South) for the area of interest, with an increasing thickness moving from N to S along the cross section (Figure 1b, Figure 2). ISP hosts a confined aquifer, but its composition is mainly uncertain due to a reduced number of available data.

Groundwater has been extensively exploited for industrial use since the early 1960s. The maximum water depletion (i.e., minimum groundwater levels) was reached in the years from the 1960s until the early 1990s, with a groundwater table more than 30 m deep in the northern sector. During this period, some underground infrastructures (car parks, subway lines) were built, sometimes with no waterproofing works [40,50,51], neglecting the possibility of any future groundwater level rise. Since the early 1990s, because of the decommissioning of many industrial sites, groundwater levels have started to rise (i.e., with a maximum rise of about 10–15 m in the northern area), generating many problems for underground infrastructures. Nowadays, the rising of groundwater is still causing severe problems, as occurs in other European urban areas, such as Paris, Barcelona and London [25–27].

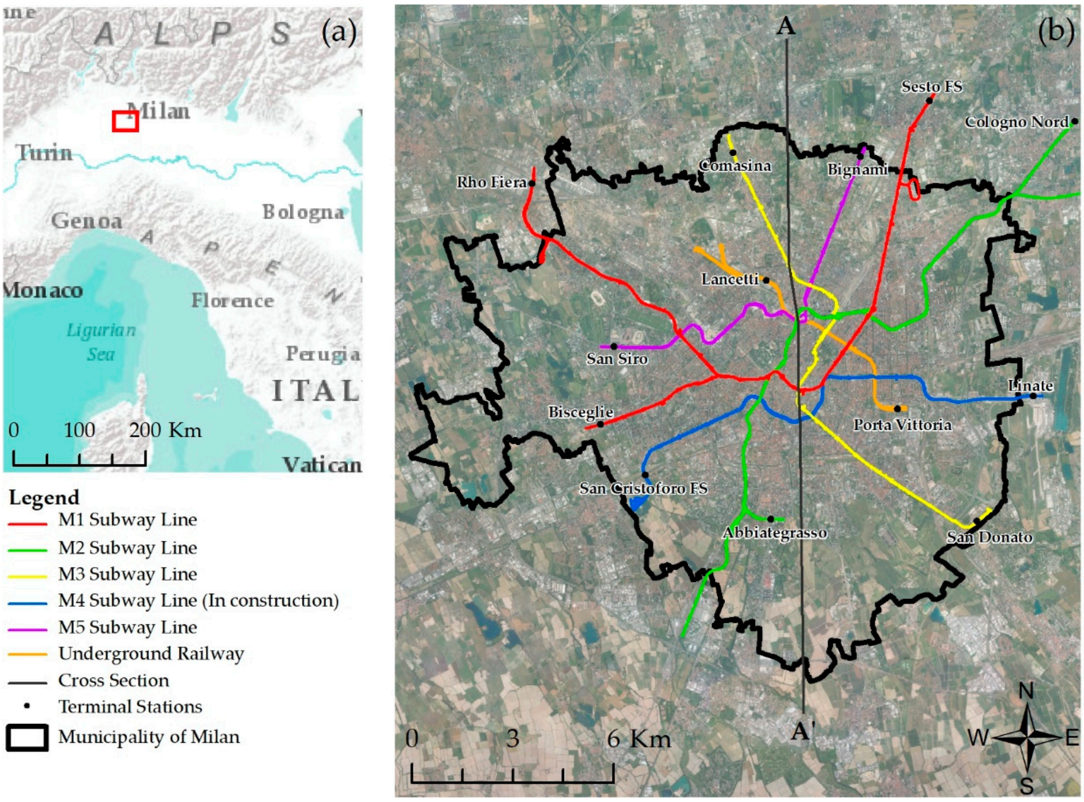

Figure 1. (**a**) Geographical setting of the study area; (**b**) the subway network of Milan; the location of the terminal stations of each line is provided. Line AA′ points to the location of the cross section represented in Figure 2. Satellite image Source: Geoportale Regione Lombardia.

As an example of the infrastructure development of the subsurface, due to its widespread presence within the study area, the subway network (Figure 1b) is described in detail below. Its construction began in the 1960s, focusing on the shallow portion of the unconfined aquifer. A top-down design mechanism was adopted, following a first-come-first-served basis approach [12,52,53]. M1 and M2 lines were built at first, with a cut and cover method to avoid interrupting the traffic on the main roads [43]. Built during the groundwater drawdown phase, they were not designed with waterproofing systems [41]. M3 line and the underground railway were built in the 1990s: due to their greater depth, they were designed with waterproofing systems. Both these constraints and the diffusion of new excavation methods [21,43] have led to the building of the most recent lines (M5 line completed in 2015; M4 line, still in construction) at greater depths; these lines have been designed to reach the most peripheral areas of the city.

Furthermore, Milan's vertical development has increased in recent years, implying a deepest subsurface occupation from the underground infrastructures. At the beginning of 2019, the new Plan of Government of the Territory (PGT) [54] was adopted. It aims at reducing soil consumption and developing new sections of subway lines. This will lead to a greater underground occupation, thus requiring a coordinated management of all the assets involved and reliable information on their location and properties.

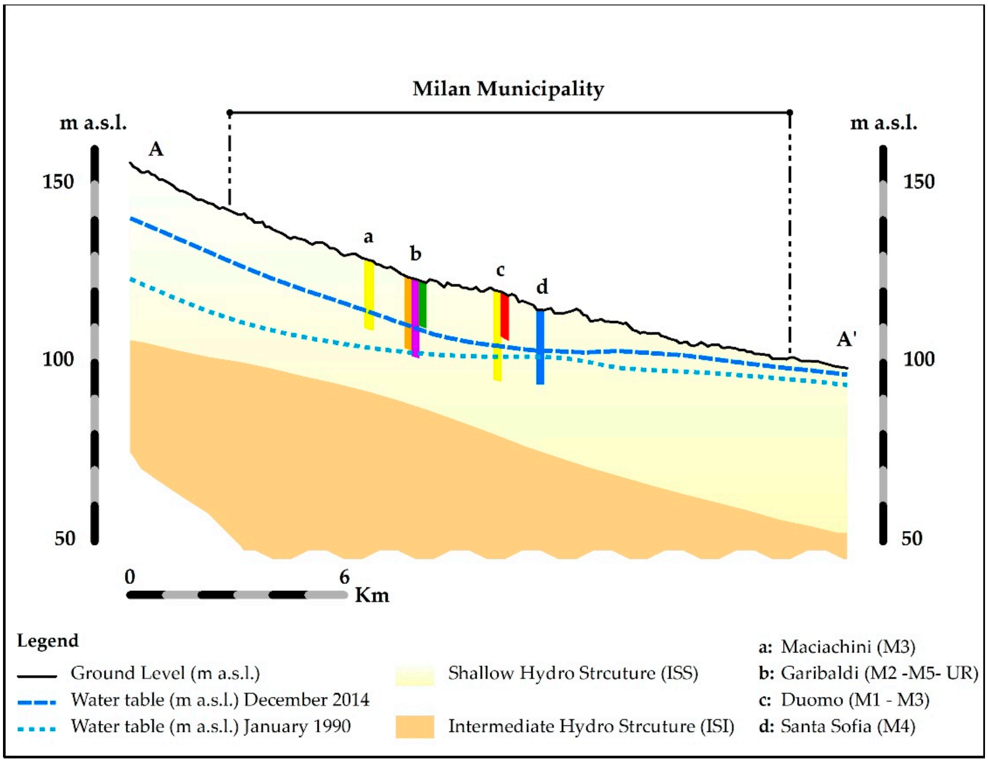

Figure 2. Hydrogeological schematic N–S cross section of the study area, showing the location of some subway stations.

3. Materials and Methods

The methodology proposed in the present paper is composed of 4 steps: (1) implementation of a 3D geodatabase for underground infrastructures (3D GDB), including the calculation of the underground volume occupied by infrastructures, (2) groundwater table reconstruction (GW), (3) calculation of infrastructure volumes (VOL) below the water table by combining the results of the previous steps, (4) evaluation of flooding of non-waterproofed infrastructures (FLOOD); the comparison between the results of this evaluation and actual flooding events, testified by local press news and photographic documentations, is used to qualitatively validate the whole methodology. A graphical representation of the methodology is given in Figure 3.

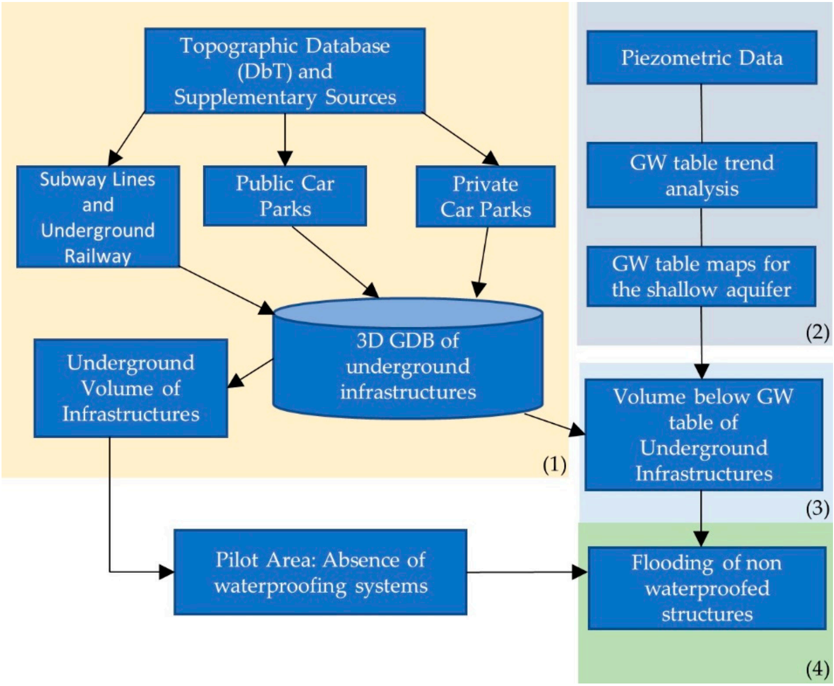

Figure 3. Flowchart of the proposed methodology.

3.1. *Implementation of a 3D Geodatabase for Underground Infrastructures*

The Topographic Database (DbT, scale 1:2000), Ref. [55] was used as the main source of information to build the 3D GDB. The DbT is an open-data basic cartographic tool owned by each municipality, used to represent the composition of the territory at the date of the air flight performed to build it. It reports the surface cartographic elements but not the underground volume occupied by infrastructures. This information resides in the urban Cadastre, a cartography which represents the inventory of the properties of the real estate units. In Italy, the Cadastre is property of the Revenue Agency: thus, it is a non-open data source. For this reason, it was not possible to consider it in this study. The DbT was shown to be useful but not sufficient in implementing the 3D GDB: thus, other supplementary sources were used to complete it. The list of public car parks is available as open data at the Municipality of Milan, while Metropolitana Milanese S.p.a, the subway managing company, only provided for this study information on the tracks of the subway lines and the underground railway.

The main fields of the GDB, common to the three types of underground infrastructures, are: Name/ID; bottom reference (m a.s.l.); depth (m); area (m^2); volume (m^3). All the underground infrastructures were considered as polygon features.

Three supplementary fields were added both for public car parks and subway lines: period of construction, the number of underground floors and location for the former; period of construction, type of infrastructure (gallery or station) and waterproofing for the latter. Information on waterproofing was uploaded only for the subway lines since this was the only category of underground infrastructures having this information. For both private and public car parks it was difficult to obtain this information.

All the data collected were processed in GIS systems, with ArcMap 10.7 [56].

3.1.1. Private Car Parks

Within the specifications of the DbT, an information layer called “dressing lines” was included; these elements are mainly used for cartographic representation: among them, ramp lines are contained. Starting from the ramp lines, ramps were digitized as polygons through a neighborhood algorithm, to estimate their areal distribution.

Subsequently, an assumption was made: if an access ramp is present, then it leads to an underground volume. A spatial analysis procedure was therefore developed, to automatically identify all the buildings adjacent to the underground access ramps, listing them as elements having subsurface occupation (Figure 4). Tests were carried out with different distances (3, 5 and 10 m) to provide the definition of a suitable distance so that the closest building could be associated with a given ramp.

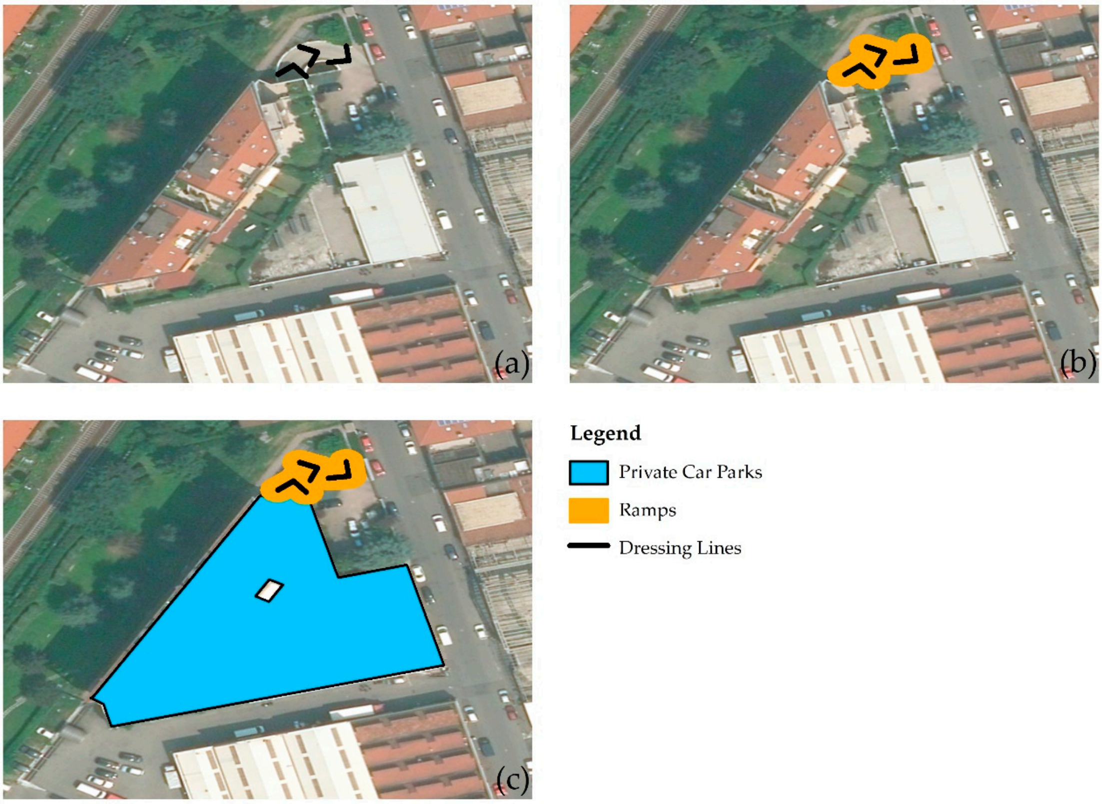

Figure 4. Schematization of the procedure to calculate the underground volume occupied by private buildings. (**a**) Identification of the dressing lines. (**b**) Digitization of the ramp polygon associated to the dressing lines. (**c**) Spatial analysis to associate the building with the ramp. Satellite image source: Geoportale Regione Lombardia.

This methodology allowed us to identify the areal extension (with the same scale as the DbT) of the possible underground occupation, whose surface is comparable with the polygon of the building, but not the occupied volume, since the depth is not available. Therefore, given future groundwater management needs, a standard depth of 5 m has so far been attributed to each element. This depth was considered exhaustive to satisfy the underground needs of each building, which were estimated as one floor. The bottom reference was calculated subtracting the attributed depth of 5 m to the Digital Terrain Model value measured at the centroid of each infrastructure.

3.1.2. Public Car Parks

The city of Milan has a list of 126 car parks classifiable as public (municipal-owned car parks, granted to private users). The perimeter of each public car park was manually digitized (time spent: three man-months) using the few elements present in the DbT (ventilation grilles, fire tanks, elevators lifts) as markers for the digitization, together with other documentary sources (press review, aerial images, public photographic archives). Thus, these elements were digitized with the same scale as the DbT. While for private car parks the subsurface occupation was estimated at one floor, these parks are characterized by a multi-story development: the number of underground floors depends on the parking needs of each area, with possible differences among different areas of the city. To estimate their volumetric impact on the subsurface, the existing number of underground floors was then considered. The total depth of each car park was assigned as follows: to the first floor, considering also the access ramp to the parking, a depth of 5 m was assigned; to all the other floors, a depth of 3 m was assigned [57]. The bottom reference of each public car park was calculated in the same way as for the private car parks.

3.1.3. Subway Lines and Underground Railway

The subway lines and the underground railway are represented in the DbT as lines, but there is no information about the altitude. Furthermore, since the DbT was updated to 2012, the M5 line, of more recent construction, does not appear.

The altimetric profiles of each subway line and of the underground railway, together with information on the average diameter of the tunnels of each track, were provided by Metropolitana Milanese S.p.a, the subway managing company. The digitization of points and of their altitude along the various sections of each line was carried out to define the lower limits of the infrastructures (bottom of the stations, intervention works and tunnels); from these limits, considering the average tunnel diameter of each line and since all the stations reach the ground level, reliable thicknesses and depths were considered. Thus, final polygons have a centimeter geometric accuracy. The M2 line and the underground railway are constituted both of superficial and underground stretches; the formers were not considered in the calculation.

3.2. Reconstruction of the Groundwater Table

Groundwater levels were provided by the local water authority (Metropolitana Milanese S.p.a); piezometric trends at each measured location were reconstructed to identify a global minimum, a local minimum, a global maximum, and a local maximum of the groundwater level time series. The period examined was between January 1990 and December 2019. Potentiometric maps for the shallow aquifer were reconstructed for the identified periods. Groundwater heads in wells were interpolated using universal kriging due to the presence of a piezometric trend (from NW to SE) [40,58–62].

3.3. Calculation of Infrastructure Volumes below the Water Table

Combining the results of the previous steps, volumes below the groundwater table and their variation over time were quantified through a spatial analysis of the available data ("Polygon Volume" and "Surface Difference" tools available in ArcMap 10.7.). The "Polygon Volume" tool was used to quantify the volumes lying below the groundwater table for private and public car parks, while the "Surface Difference" tool was used for subway lines. The bottom of underground infrastructures was considered as the reference limit to quantify the volume of an infrastructure lying below the groundwater table.

3.4. Evaluation of the Impact of Groundwater on Non-Waterproofed Infrastructures in a Pilot Area

Following the calculation of infrastructure volumes below the groundwater table, a pilot area was identified, including the three categories of underground infrastructures, to evaluate the impact of groundwater on these infrastructures. If a lack of an appropriate waterproofed system emerged, these infrastructures were considered as vulnerable to infiltrations or flooding. Stretches of lines M1 and M2 fall within this area, as well as some of the oldest public car parks included in the GDB. The infrastructures identified as flooded were compared to available local press news and photographic documentations. Their matching can be considered as a qualitative validation of the whole methodology here proposed.

4. Results

4.1. 3D GDB Implementation and Analysis

The application of the methodology developed to identify private car parks led to the insertion into the GDB of 11,283 buildings out of 53,041 among those included in the DbT. This result was obtained using an association distance of a building with a given ramp of 5 m, which emerged as the optimal distance for the study area. Their territorial distribution shows a higher concentration of underground occupation in areas urbanized after post-war reconstruction, in line with the development of the city urban fabric. An example of their features is provided in Table 1.

Table 1. Main features of selected private car parks (PrCP) located in the study area.

Name/ID	Bottom Reference (m a.s.l.)	Depth (m)	Area × 10^3 (m^2)	Volume × 10^3 (m^3)
PrCP1	119.32	5	0.12	0.59
PrCP100	117.27	5	0.23	1.17
PrCP1000	112.99	5	1.37	6.87
PrCP10000	127.94	5	0.14	0.71
…	…	…	…	…
PrCP11283	127.52	5	0.48	2.39
Total Parks: 11,283				45,100.96

A brief example of the list and features of the 126 public car parks is provided in Table 2. The overall list is presented in Table S1 (Supplementary Materials). The highest density of underground car parks is in the city center, where the oldest (<1990) and the most recent (2007–2014) car parks were built. Furthermore, these parking lots present a higher depth with respect to the ones located in the most peripheral areas of the city, built mostly from the 1990–2002 period onward.

Table 2. Main features of some of the public car parks located in the study area.

Name	Bottom Reference (m a.s.l.)	Depth (m)	Area × 10^3 (m^2)	Volume × 10^3 (m^3)	Period of Construction	Number of Floors	Location
Silla	131.3	5	5.82	29.1	2002–2007	1	North of Milan
Erculea	100.91	17	1.3	22.10	<1990	5	Downtown
Risorgimento Nord	96.9	20	1.43	28.6	2007–2014	6	Downtown
Ciclamini/Margherite	111.5	8	3	24	1990–2002	2	West
…	…	…	…	…	…	…	…
Cascina Bianca	106.2	5	7.88	39.4	2002–2007	1	South of Milan
Total Parks: 126				5157			

An example of the main characteristics contained in the 3D GDB for the subway lines and the underground railway is provided in Table 3.

Table 3. Main features of some stretches of the subway lines and underground railway located in the study area.

Name	Bottom Reference (m a.s.l.)	Depth (m)	Area × 10^3 (m^2)	Volume × 10^3 (m^3)	Period of Construction	Type	Waterproofed
Duomo (M1)	107.64	12.47	5.56	69.33	<1990	Station	No
Sant'Agostino (M2)	99.12	17.35	1.37	23.77	<1990	Station	No
Duomo (M3)	95.7	25.05	4.59	114.98	1990–2002	Station	Yes
Linate (M4)	98.91	11.1	4.25	47.17	2021–2023	Station	Yes
…	…	…	…	…	…	…	…
Lotto (M5)	98.47	26.28	2.41	63.33	>2014	Station	Yes
Repubblica–P.ta Venezia (UR)	100.9	8.5	6.15	52.27	1990–2002	Gallery	Yes
Total elements: 388				13,702.67			

A map showing the location and volumes of all the underground infrastructural elements contained in the 3D GDB is provided in Figure 5. Moreover, a more detailed visualization of the contents of the 3D GDB is made available through a WebGIS service (https://arcg.is/HHWDi0). Larger volumes for a single element reach up to more than 100×10^3 m^3 and refer to subway elements; smaller volumes are less than 10×10^3 m^3 and mainly refer to private car parks. However, total volume for each type of infrastructure reveals that private car parks occupy larger volumes (45×10^6 m^3) than railways (14×10^6 m^3), followed by public car parks (5×10^6 m^3).

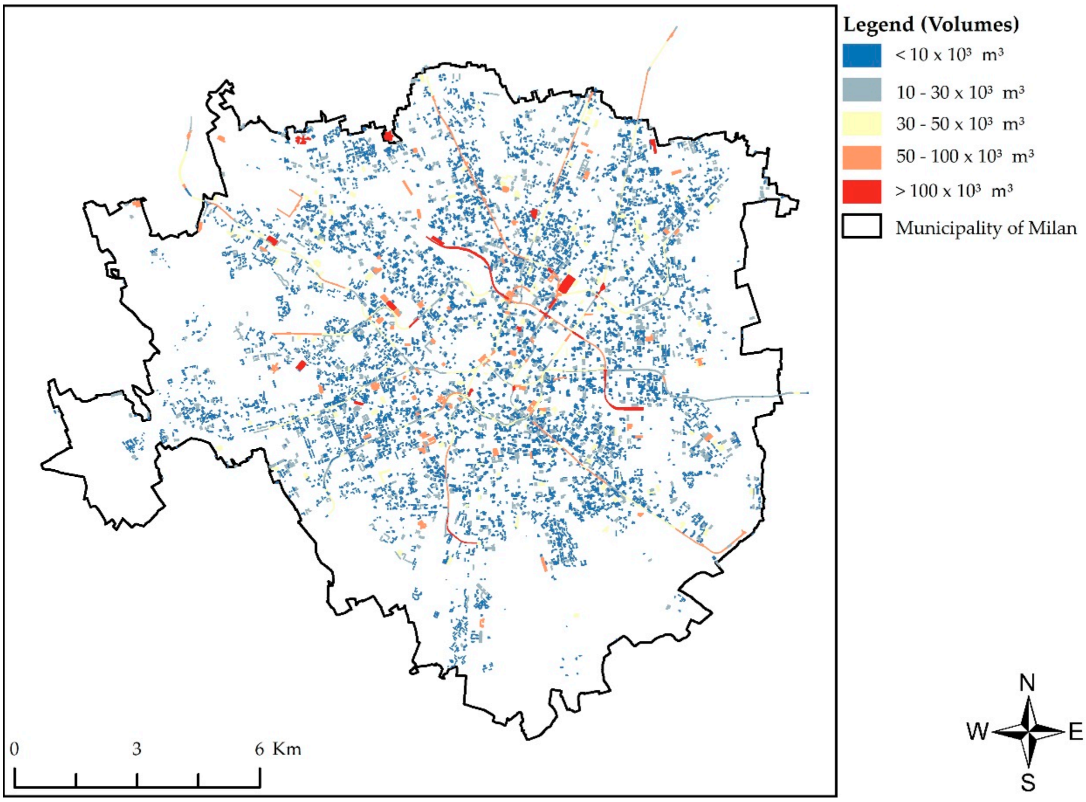

Figure 5. Location and volumes of all the infrastructural elements contained in the 3D geodatabase (GDB) (private and public car parks and subway lines).

4.2. GW Table

Ten monitoring wells (MW) (Figure 6b), distributed across the domain, were selected to perform the piezometric trend reconstructions. As described in Section 3.2, four periods were identified: January 1990 (Jan90) as the global minimum of the whole considered groundwater level time series; December 2002 (Dec02) as a local maximum of the groundwater level time series; September 2007 (Sep07) as a local minimum; December 2014 (Dec14) as the global maximum. GW table maps for the shallow aquifer (ISS) for these four periods are provided in Supplementary Materials (Figures S1–S4). Jan90 could be identified as the overall starting point of the increasing trend consequent to the industrial decommissioning which began in the early 1990s [58,63]. However, this is not the historical global minimum, which occurred at the end of the 1970s, determined by an intense industrial exploitation [50]. As visible in Figure 6a, monitoring wells located in the northern part of the domain registered a wider oscillation of the groundwater table than the southern ones. Reduced oscillations in the southern area are due to geological and hydrogeological reasons: changes in sediment permeability from coarse (i.e., gravel and sand) to fine (i.e., silt and clay) induce groundwater to outflow, forming numerous lowland springs [64], and thus constraining groundwater oscillations.

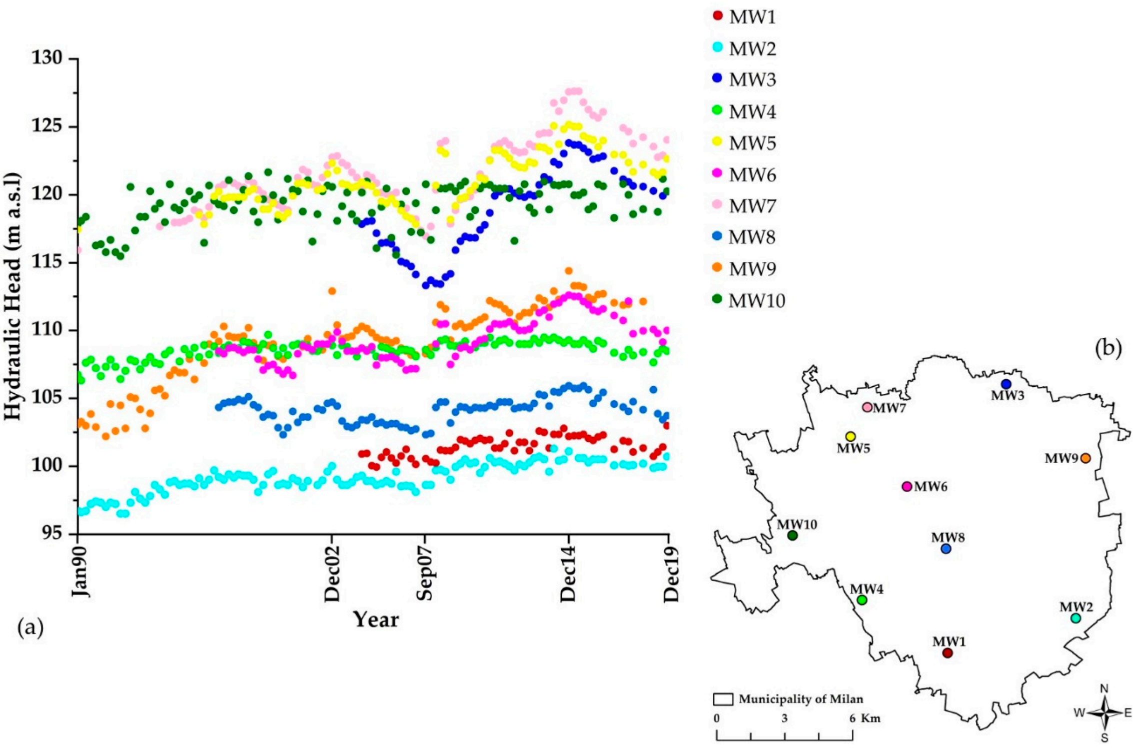

Figure 6. (**a**) Monitoring wells (MW) time series for the considered period (January 1990–December 2019). (**b**) Location of the MWs in the study area.

A general rising trend is identifiable in the period considered, except for seasonal trends emerging in the local minimum and the global maximum periods.

4.3. Infrastructure Volumes below the Water Table

The results in Figure 7 are provided only for the local minimum (Sep07) and the global maximum condition (Dec14): the majority of underground infrastructures were built in these periods, thus facilitating the comparison of the results.

Volumes below the groundwater table for private car parks were identified both in minimum and maximum groundwater level conditions (Figure 7). In the minimum groundwater level period (Sep07), a few volumes were found to be below the groundwater table (a total of 0.32×10^6 m^3), most of which were concentrated in the western part of the study area. In maximum groundwater level conditions (Dec14), the total amount of volumes below the groundwater table increased, reaching 1.12×10^6 m^3, and their spatial distribution expanded toward the south east portion of the area. Furthermore, a few volumes below the groundwater table also emerged in the northern sector of the study area.

As regards public car parks, in the northern part of the area, the unsaturated zone of the aquifer is wider than in the southern part (Figure 2); therefore, only deep volumes can actually be reached by the groundwater table. Most of the public car parks in the northern part of the area are only developed on two underground floors, therefore they do not appear to be within the range of the groundwater table oscillation. In contrast, in the southern part of the city, more car park volumes lie below the groundwater table (Figure 7). Particularly in the western part, where car park depth is limited to two underground floors, the analysis revealed that car park volumes are below the groundwater table only during the maximum period. On the other hand, in the downtown, the car parks can have up to six floors. Because of this, the analysis identified several car parks with volumes below the groundwater table also during the minimum period. In the southernmost part of the area, most of the car parks range between one and two floors, while only in a few cases do they reach three floors.

In the latest case, the analysis showed volumes below the groundwater table during both minimum and maximum conditions.

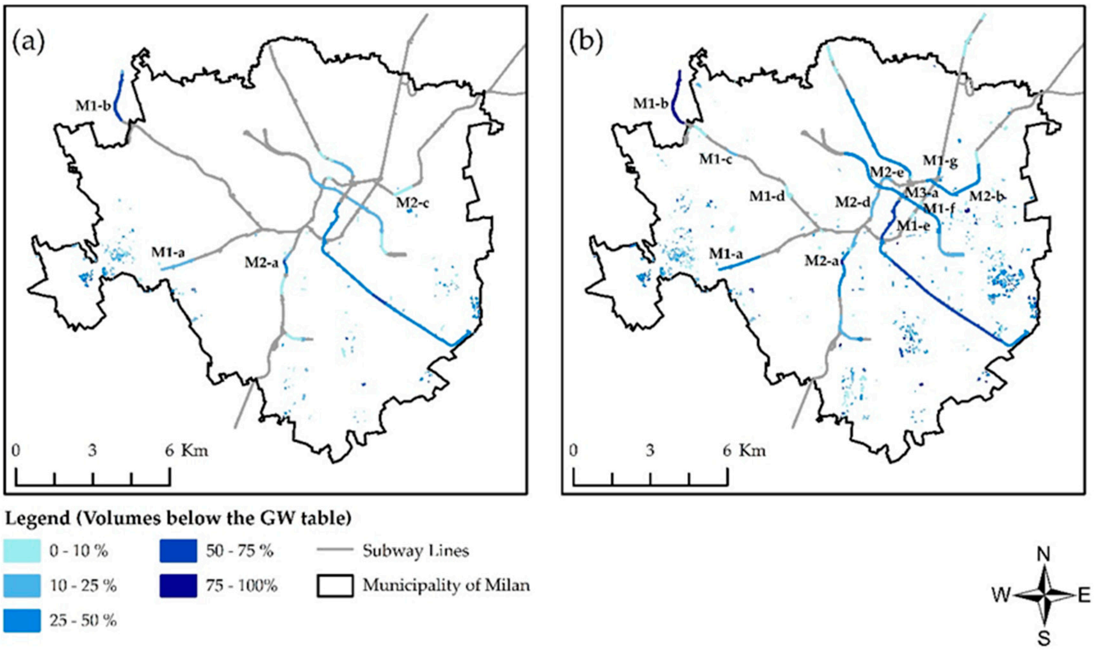

Figure 7. Volumes lying below the groundwater (GW) table for the local minimum of Sep07 (**a**) and for the global maximum of Dec14 (**b**). Colour coding indicates percentages of the volumes below the groundwater table.

As regards the M1 subway line, its westmost stretch, close to Bisceglie station (M1-a, Figure 7), was frequently below the groundwater table. Apart from Jan90, when this section was still under construction, some portions of this stretch always revealed an interaction with the groundwater table. Volumes below the groundwater table were also identified in the most recent northern stretch of this line, including Rho Fiera and Pero stations (completed in 2005) for both Sep07 and Dec14 periods (M1-b, Figure 7). Furthermore, during the maximum groundwater level periods, some similar situations emerged in different areas: in particular, in the northern stretches of the line, from Bonola to Uruguay stations (M1-c, Figure 7b), and in the stretch between QT8 and Lotto stations (M1-d, Figure 7b). In the downtown areas, a few volumes below the groundwater table emerged in the maximum periods between Palestro and Porta Venezia (M1-e, Figure 7b), Porta Venezia and Lima (M1-f, Figure 7b) and between Loreto and Pasteur stations (M1-g, Figure 7b).

For the M2 line, the section around Sant'Agostino station (M2-a, Figure 7) emerged as the stretch that most frequently reveals volumes below the groundwater table, during all the considered periods. From Dec02 onward, the section between Loreto and Udine stations (M2-b, Figure 7b), particularly between Piola and Lambrate stations (M2-c, Figure 7), showed some volumes below the groundwater table. During the maximum groundwater levels periods, volumes below the groundwater table also emerged in the downtown areas between Lanza and Moscova (M2-d, Figure 7b), and between Garibaldi and Gioia stations (M2-e, Figure 7b).

The M3 line was inaugurated around the middle of 1990, so Jan90 was not evaluated in the analysis. Except for Centrale and Repubblica stations (M3-a, Figure 7b), located in the downtown area, the central part of the line was always below the groundwater table. A similar situation was for the southern stretch of the line.

The underground railway was inaugurated in 1997. As for the M3 line, volumes below the groundwater table were identified along most of the line.

The analysis of the volumes below the water table was not performed for M4 and M5 lines. The M4 line is under construction, and its completion is expected to be between 2021 and 2023. The M5 line was inaugurated in 2015, so after the identified groundwater local and global periods.

The results that emerged in this study for the subway lines and the underground railway are consistent with what was discussed by Colombo [65], who identified the M1-a, M1-c to M1-g, M2-a and M2-c to M2-e areas as the most critical concerning groundwater/infrastructure interactions.

The evolution of the volumes lying below the groundwater table over time is reported in Figure 8 as percentages of the total volume for each type of infrastructure for the four periods considered. A general increasing trend of the volumes below the water table has been observed, connected to the groundwater rising trend visible in Figure 6a, with marked seasonal oscillations for the local minimum of Sep07 and the global maximum of Dec14. Percentages are minimal for private car parks, due to their reduced depth, while an increase is visible for public car parks and subway lines. For these latter cases, the increase is related to their period of construction, with the more recent lines showing a higher percentage of volumes below the water table.

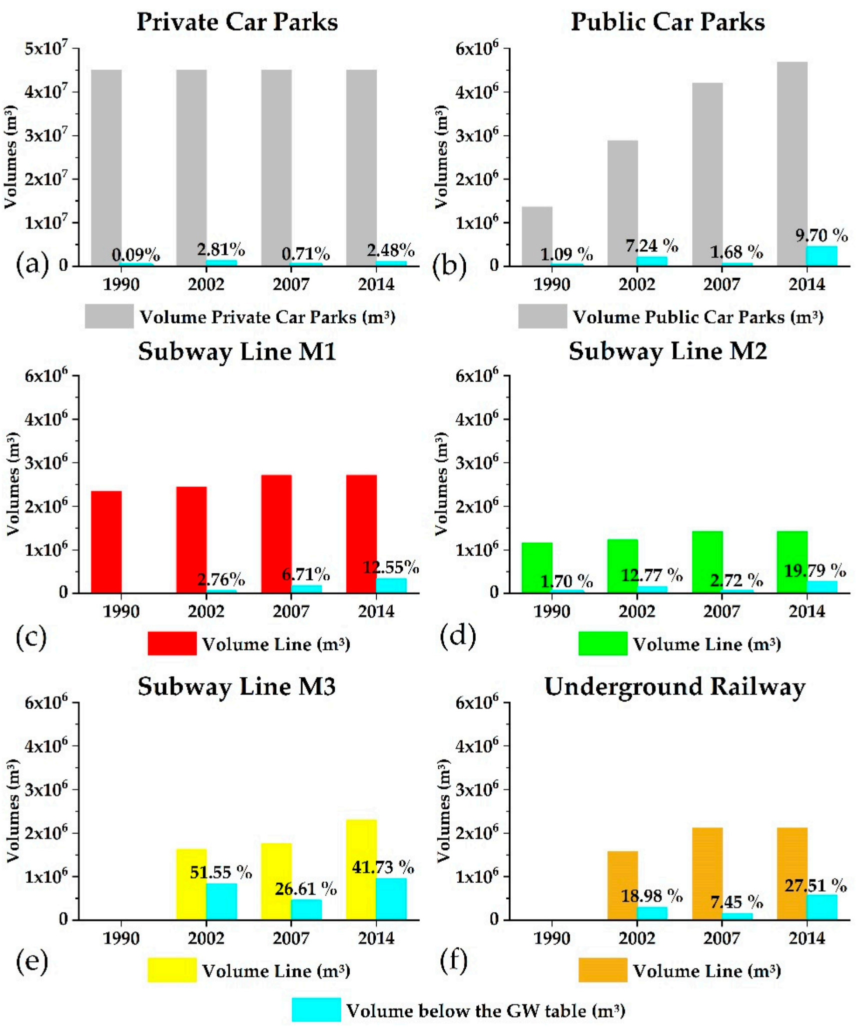

Figure 8. Volumes and portions below the groundwater table (cyan expressed as percentages of the total volume) over time for: (**a**) Private Car Parks, (**b**) Public Car Parks, (**c**) Subway Line M1, (**d**) Subway Line M2, (**e**) Subway Line M3, (**f**) Underground Railway. *Y*-axis scale is the same for all the categories, except for Private Car Parks, where 10^7 has been kept as an order of magnitude.

4.4. Impact of Groundwater on Non-Waterproofed Infrastructures in a Pilot Area

The impact of groundwater on non-waterproofed infrastructures was evaluated for a pilot area of 2.56 Km^2 (Figure 9), located in the downtown area, including five public car parks, six stations and eight stretches of the subway lines M1 and M2. Except for Sant'Ambrogio car park, which was inaugurated in 2014, the other public car parks were theorized as non-waterproofed. In this area, volumes lying below the GW table were not identified for private car parks.

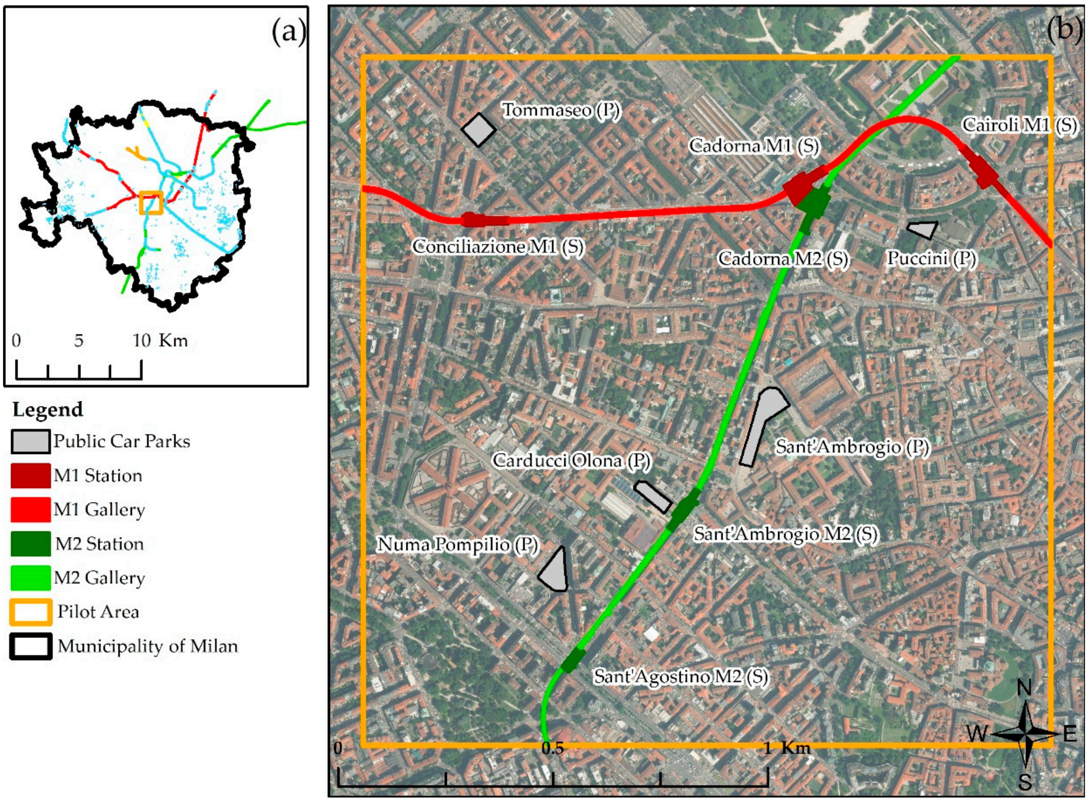

Figure 9. (**a**) Geographical setting of the pilot area. Locations of volumes lying below the GW table for the maximum groundwater level condition of Dec14 are shown. (**b**) Underground infrastructures within the pilot area. (P) means public car park; (S) means station. Satellite image Source: Geoportale Regione Lombardia.

A graphical representation of the volumes lying below the groundwater table for all the periods considered is provided in Figure 10, indicating estimated infrastructure flooding due to non-waterproofing. Quantifying the flooding would require also considering construction methods and material used, which is beyond the aims of this work. Therefore, in this work, flooding is intended just as a qualitative validation (i.e., infrastructures which can present infiltrations or flooding).

The results for all the infrastructural elements considered are summarized in Table 4. Concerning subway stations, Sant'Agostino (line M2) was the most affected, followed by Sant'Ambrogio (line M2), which was only slightly affected. Accordingly, the M2 line stretches to/from and between these stations were estimated to be flooded. On the contrary, line M1 stretches and stations, located in the northern portion of the pilot area, did not reveal volumes below the water table in each of the periods considered (Figure 10), as occurred also for the considered northern portion of the M2 line (Figure 10), due to their shallower depth.

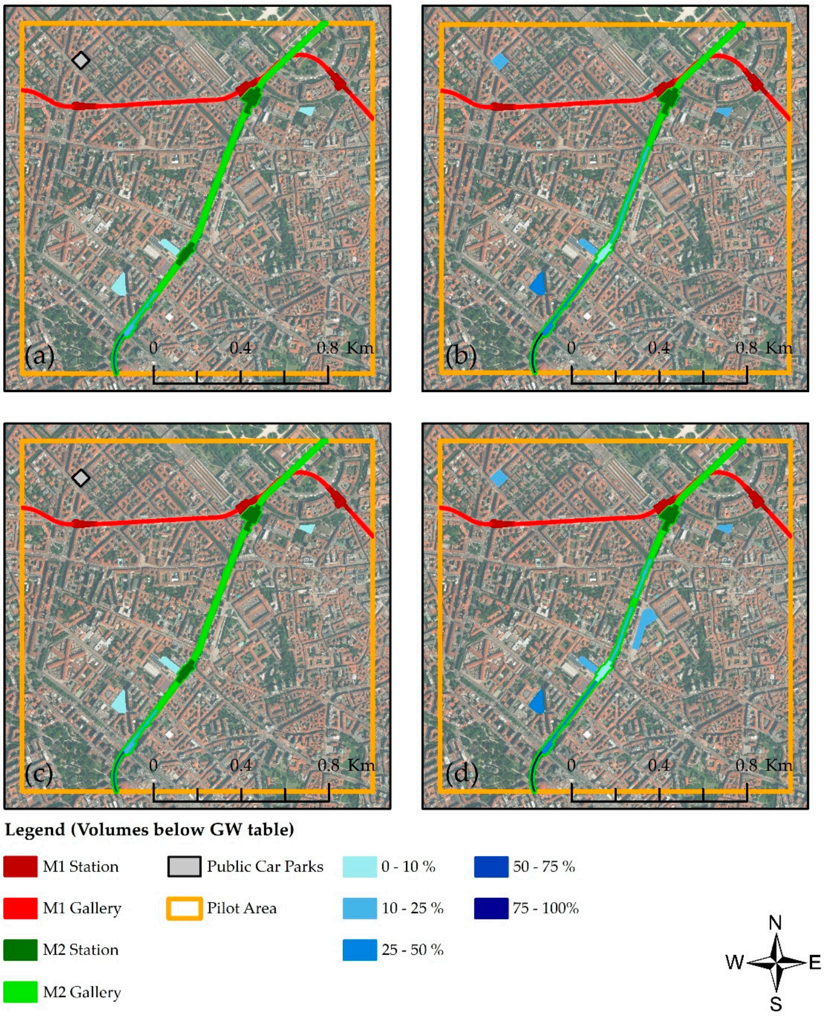

Figure 10. Volumes lying below the GW table in (**a**) Jan90, (**b**) Dec02, (**c**) Sep07, (**d**) Dec14. Colour coding indicates percentages of the volumes below the groundwater table. Satellite image Source: Geoportale Regione Lombardia.

Table 4. Features and volumes below the GW table of the underground structures within the pilot area. V Jan90 (%), V Dec02 (%), V Sep07 (%) and V Dec14 (%) refers to the percentage volume below the GW table of the underground infrastructures for each of the periods considered. (V) means volume; (G) means gallery; (P) means underground car park; (S) means station. Sant'Ambrogio car park was considered only in the final period because it was completed in 2014.

Type	Name	Depth (m)	Area × 10^3 (m^2)	Volume × 10^3 (m^3)	Period of Construction	V Jan90 (%)	V Dec02 (%)	V Sep07 (%)	V Dec14 (%)
S	Cadorna M1	10.65	3.53	37.59	<1990	0	0	0	0
S	Cairoli M1	10.16	3.40	34.54	<1990	0	0	0	0
S	Conciliazione M1	9.5	2.22	21.09	<1990	0	0	0	0
S	Cadorna M2	10.31	4.06	41.86	<1990	0	0	0	0
S	Sant'Agostino M2	17.35	1.37	23.77	<1990	16.47	35.79	16.50	34.85
S	Sant'Ambrogio M2	12.77	2.41	30.77	<1990	0	3.46	0	9.79
G	Pagano–Conciliazione M1	6.5	2.34	15.21	<1990	0	0	0	0
G	Conciliazione–Cadorna M1	6.5	6.18	40.17	<1990	0	0	0	0
G	Cadorna–Cairoli M1	6.5	3.55	23.07	<1990	0	0	0	0
G	Cairoli–Cordusio M1	6.5	1.4	9.1	<1990	0	0	0	0
G	Porta Genova–Sant'Agostino M2	7	1.08	7.56	<1990	63.76	113.88	65.68	106.66
G	Sant'Agostino–Sant'Ambogio M2	7	3	21	<1990	12.62	42.77	12.40	49.88
G	Sant'Ambrogio–Cadorna M2	7	6.4	44.8	<1990	0	13.76	0	20.65
G	Cadorna–Lanza M2	7	3.98	27.86	<1990	0	0	0	0
P	Carducci Olona	17	3.42	58.14	<1990	4.26	17.63	3.75	20.79
P	Numa Pompilio	17	4.07	69.27	<1990	8.65	27.72	8.28	28.18
P	Puccini	20	1.68	33.65	<1990	3.56	19.27	2.84	22.69
P	Sant'Ambrogio	17	7.41	125.93	2007–2014	—	—	—	22.40
P	Tommaseo	17	3.15	53.60	<1990	0	13.29	0	19.85

An additional 3D reconstruction of the historical evolution of the most affected Sant'Agostino M2 station was realized (Figure 11). During groundwater maximums (Figure 11c,e), the gallery stretches to and from the station was completely submerged by the groundwater table, and thus flooded. Moreover, the flooding of the station and galleries is estimated, with a lower extent, also for groundwater minimum periods. Thus, Sant'Agostino station can be considered as being constantly impacted by flooding. This assumption is confirmed by actual flooding events that frequently happened in the last 10 years, as documented by local press and photographic documentations (Figure 12).

Concerning public car parks, due to their deeper structures, volumes below the water table have been identified in all the considered periods, apart from Tommaseo, which is above the groundwater table under minimum-level conditions (Figure 10). As regards Numa Pompilio, as for Sant'Agostino station, the identified flooding is confirmed by photographic documentation (Figure 12c). Some waterproofing works have been carried out in the last decade to counteract this situation (Figure 12d). On the contrary, flooding episodes have not been documented for Sant'Ambrogio car park, which, being more recent, was designed as being waterproof. This approach should also be applied in the other areas that emerged as critical from this work.

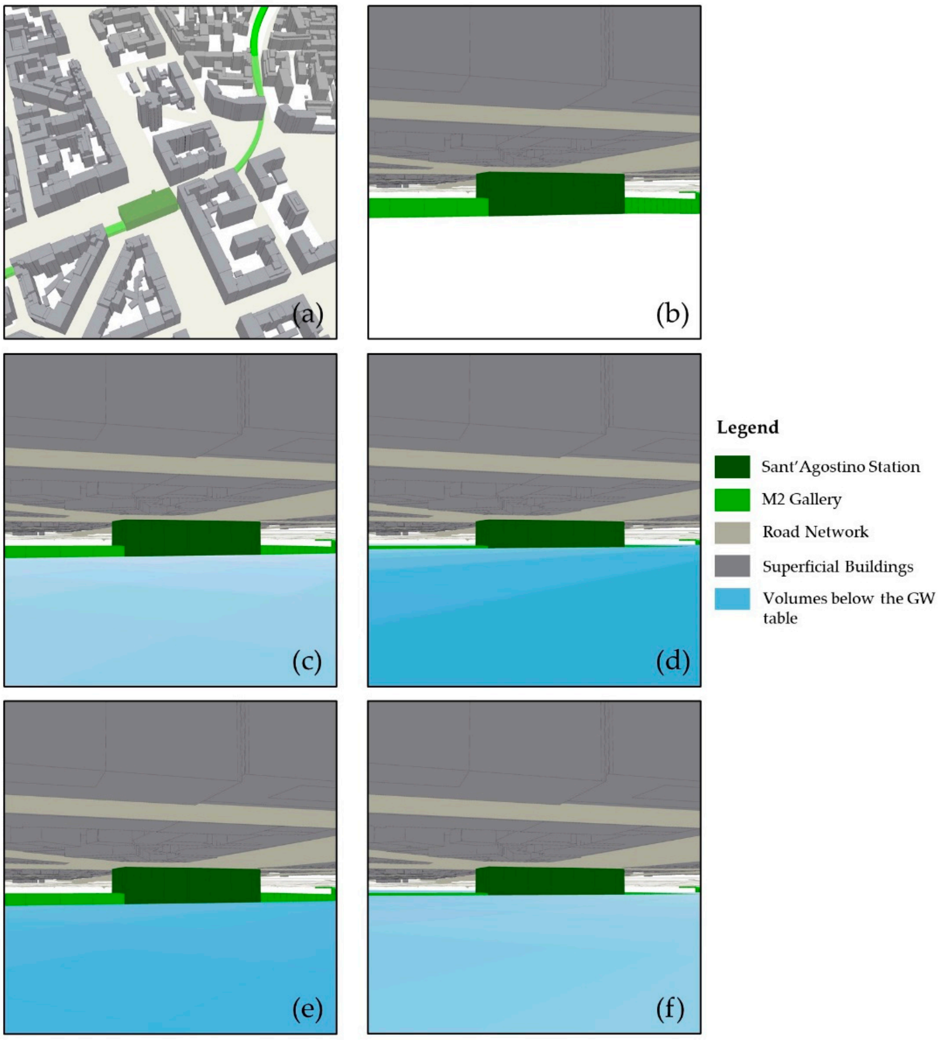

Figure 11. (**a**) Three-dimensional surface reconstruction close to Sant'Agostino station. Sant'Agostino station is visible below the road network. (**b**) Three-dimensional underground reconstruction of Sant'Agostino station. Volumes below the GW table of Sant'Agostino station in (**c**) Jan90, (**d**) Dec02, (**e**) Sep07, (**f**) Dec14. Images were realized with ArcGIS Pro.

La falda sale, acqua alta nel metrò
Verde a 20 all'ora in Sant'Agostino

ILARIA CARRA

VENTI chilometri all'ora, al massimo. La metropolitana Verde è di nuovo a mollo: negli ultimi giorni, centimetro dopo centimetro, alla fermata di Sant'Agostino la falda è tornata a rialzarsi e ha allagato i binari. Tanto che i segnali lungo il tracciato obbligano i macchinisti a dimezzare la velocità del treno. «Misura precauzionale» dicono i tecnici. Rischio di effetto aquaplaning, ancora una volta, che rilancia l'urgenza dell'intervento

Nel tratto verso Sant'Ambrogio servono le idrovore per tenere il livello sotto controllo

I precedenti

PIOLA
Un anno e mezzo fa il Comune intervenne tra Piola e Lambrate dove si verificò l'ennesimo allagamento

SONDRIO
Non fu la falda, ma l'esondazione del Seveso a allagare la stazione Sondrio della Gialla quasi tre anni fa

SANT'AGOSTINO
Già nel 1998 c'erano infiltrazioni: in settembre Sant'Agostino andò in tilt a causa dell'acqua alta 40 centimetri

Figure 12. (**a**) Newspaper article of "La Repubblica" (2 July 2013), dealing with flooding episodes in Sant'Agostino station. (**b**) Flooding evidence in Sant'Agostino station (8 September 2020). (Image credits to the authors). (**c**) Flooding evidence in Numa Pompilio public car park. (**d**) Absence of flooding evidence after waterproofing works in Numa Pompilio public car park. (**c**,**d**): images were provided by Rete Irene.

5. Discussion

An urban transformation, which also involves the underground aspects, is taking place for the city of Milan. A detailed inventory of all the underground infrastructures is thus required.

The GDB has allowed us to gather part of the wide array of urban data, usually coming from different sources (institutions, stakeholders, public and private owners) [24,33], standardizing dissimilarities among data to properly settle them for groundwater management needs. Due to the database's simple and updatable structure, data that with time could become available in the future will in fact be rapidly integrated with the already existing information. Its realization has been aided by Geographic Information Systems (GIS): their capacity for storing, analyzing and managing all types of geographical data [66,67] has allowed us to easily collect information coming from different sources in a single structure; moreover, the underground infrastructures were accurately reconstructed according to their real depths and volumes.

The methodology applied to define the underground occupation of private buildings (private car parks) is, to the best of our knowledge, an element of novelty; it attempts to fill a lack of information through a spatial analysis procedure, exploiting all the cartographic content available in the DbT. However, it still requires a phase of refinement. Indeed, in some cases, the underground volumes may be overestimated, as for those ramps that have a superficial development but do not lead to underground car parks (instead leading into buildings). In other cases, the underground volumes may be underestimated: the methodology fails to highlight those access ramps that fall within the perimeter of the building and therefore are not visible in the creation phase of the DbT; however, this latter case is not a very common building typology for the study area considered. Future developments will concern the consequent elimination of the overestimated elements.

The application of the methodology for the city of Milan was possible due to the availability of the DbT data distributed by the "Decimetro" geoportal [55]. The DbT is developed according to the European Standards (INSPIRE) [68]: this contributes to the replicability of the procedure in other study areas. Other factors are needed to strengthen the application of this methodology elsewhere: the availability of the same typology of data, a strict collaboration among institutions, the presence of a policy aimed at stimulating the use of open-data, and the expertise of using and extracting valuable information from data [37]. The association distance between the ramp and the building adopted for the city of Milan may not be suitable for other urban realities, thus making a previous site-specific calibration necessary.

The integration of the DbT with other supplementary sources brings out a lack of collaboration among institutions, typical of urban data management [24,33]; a closer cooperation among institutions would contribute to easily managing data both for urban underground planning and groundwater management aspects.

The GDB application has thus allowed us to evaluate how the subsurface volumes lying below the groundwater table have changed among time.

In general, in the northern part of the study area, considering an assigned depth of five meters, and a higher depth of the groundwater table, private car parks do not present volumes below the groundwater table. However, in a few cases, volumes lying below the groundwater table were also identified in the northern sector during maximum groundwater levels. This was associated with problems related to the Digital Terrain Model, which can be not fully representative of the ground level at a given point. This can be considered as a limit of the methodology: however, this problem emerged only in a few isolated situations.

The congestion of public car parks in the downtown Milan area is related to a high demand for infrastructure [12], due to socio-economic needs: the majority of the economic activities is located in the city center [47,54]. The volumes of the deepest infrastructures were shown to lie below the groundwater table: therefore, future infrastructures in this area should be planned with adequate waterproofing techniques. The reduced subsurface volume in the peripheral areas is related to a decreased socio-economic demand: despite this, as for the private car parks, volumes lying below the groundwater table were identified, in particular when the hydraulic head was higher. This is due to hydrogeological reasons: in the southern portion of the study area, the groundwater table has always been historically close to the ground level due to the presence of fine deposits (i.e., silt and clay) with low values of hydraulic conductivity [40,69–72], which force groundwater to reach the ground level; in the western area, the presence of clay lenses determines the existence of a perched aquifer located around 6–8 m below ground level, with strong seasonal oscillations [73]. An overall reduced presence of subsurface volumes (Figure 5) in these peripheral areas, compared to the downtown, is also amenable to these reasons.

The majority of the subsurface volumes lying below the groundwater table for the subway line M1 is in the northern stretch, between Rho Fiera and Pero stations (M1-b): their construction method differs from that used for the rest of the line; these two stations were built at greater depths. For the same reason, Sant'Agostino station was revealed as the most recurring area below groundwater level for M2 line: its two rails were built as overlapping pipes, thus determining a major depth of subsurface occupation. As determined by the focus on the pilot area, in Dec02 and Dec14, the considered stretch of gallery from Porta Genova to Sant'Agostino (M2-a) was completely submerged, with the groundwater level above the top of the gallery. The stretch between Loreto and Udine stations (M2-b) was revealed as another critical area. In particular, the section between Piola and Lambrate stations (M2-c) was subjected to waterproofing works during the summer of 2019 to overcome flooding problems. Since these lines were built without any impermeabilization, the increase in stretches lying below the groundwater table due to groundwater rising, both for the M1 and M2 lines, should be monitored by the subway managing company. Due to their depth, M3 line and the underground railway revealed a high percentage of subsurface volumes below the groundwater level: to overcome this problem, they were designed with waterproofing systems; M3's interaction with groundwater in the southern sector of the domain is amenable both to a deeper development of the line and a closer elevation of the groundwater table to the ground level.

As reported in Section 4.3, the methodology allowed us to verify what was already described in a previous work [65], where M1-a, M1-c to M1-g, M2-a and M2-c to M2-e areas were already pointed out as the most critical concerning groundwater/infrastructure interactions. At the same time, as reported in Section 4.4, flooding evidence, also reported by local press reviews, occurred where the oldest underground infrastructures, showing volumes below the water table, were designed without waterproofing techniques. This acts as a qualitative validation both of the methodology used to implement the GDB and its usefulness in groundwater management. In the future, citizen science approaches [74–77] or social media (i.e., tweets of metro passengers) could be exploited to validate the methodology, thus enlisting the public in organized scientific research. Both the city administrations and private companies could benefit from the implementation of this methodology, identifying the main critical areas of interaction, thus properly planning future underground development or adopting remediation strategies if necessary, especially focusing on the oldest non-waterproofed infrastructures. The GDB has in fact allowed us to analyze the interaction between groundwater and underground infrastructures both at a city scale and at a more detailed level.

The integration of the GDB with numerical groundwater flow models will make it possible to define future scenarios of interaction according to the trend of the piezometric levels. The infrastructural elements have both an active and passive effect on groundwater [41–43,78–84]. This contributes to characterizing urban modelling as a specific branch of hydrogeology, with its own time, scales, and dynamics of the hydrogeological processes [85]. Thus, this information needs to be analyzed and combined together with the large set of geological, hydrological, geomorphological and other features [86] necessary to detail a complete urban conceptual model for the domain: this is an important step, as the conceptual model is the basis of an appropriate groundwater management plan. Using a standardized 3D GDB, the urban conceptual model would not need to be frequently revised, a both time- and cost-consuming activity [85].

The implementation of a 3D vision of the volumes below the groundwater table over time (Figure 11) was revealed to be a comprehensible tool to evaluate this phenomenon: an increased use of these instruments will both guarantee a complete 3D vision of the subsurface and a proper 3D urban planning. The use of the GDB in a wider coupled 3D GIS–groundwater model (such as MODFLOW [87] or FEFLOW [88]) system will be thus efficient to plan sustainable and integrated groundwater management, helping local stakeholders and regulators to manage not only groundwater, but all the underground resources in a more efficient and sustainable way. To this aim, the use of tools as WebGIS services could guarantee an effective way of spreading the existing information.

Moreover, an easy identification of the main underground infrastructures will help to overcome the lack of coordination, lack of planning and lack of understanding of the other domains among the different stakeholders [19,89,90], thus avoiding jeopardizing the potential of the resources below the city [19]. Considering the urban development declared in the Plan of Government of the Territory, the GDB would contribute to maintaining the underground potential, guaranteeing a long-term management of the urban underground space.

6. Conclusions

This work dealt with the proposal of a methodology to quantify volumes of underground infrastructures lying below the groundwater table for Milan metropolitan area, which has been affected by an interaction between groundwater and underground infrastructures in the last few decades. This study has allowed us to:

1. Create a detailed inventory of the underground infrastructures through a standardized 3D geodatabase, to manage the existing data and incorporate new information in an efficient and easy way. This was realized using open data as the main source of information.
2. Identify the main areas where infrastructural volumes lie below the groundwater table, and to evaluate how this situation has varied among time according to groundwater trends, with attention

to non-waterproofed infrastructures. This, to the best of our knowledge, has been done for the first time both for private and public car parks.

3. Provide to the decision-makers and stakeholders a useful tool to properly plan and manage the future urban underground development of Milan metropolitan area, in relation also to groundwater aspects.

An integration of this approach with groundwater numerical models will contribute to improving urban groundwater management. Through the analysis of the piezometric trends, different groundwater level scenarios will be tested, thus evaluating the effects of climate change or of possible variations in the pumping rates. Future perspectives will also consider the creation of a script to automatize the calculation both of groundwater levels and underground volumes; in this way, the urban conceptual model could be managed as a dynamic construct, always including in the analysis new hydrogeological and infrastructural elements. In the end, empowering the use of tools as 3D GIS and WebGIS services could be a way to make the information effectively available to the stakeholders, thus contributing to proper urban planning. Furthermore, the methodology used here could be applied in other similar case studies worldwide.

Supplementary Materials: The following are available online at http://www.mdpi.com/2220-9964/9/10/0609/s1, Table S1: Complete list and features of the underground car parks located in the study area, Figure S1: GW table map for Jan90, Figure S2: GW table map for Dec02, Figure S3: GW table map for Sep07, Figure S4: GW table map for Dec14, link to the WebGIS service.

Author Contributions: Davide Sartirana and Mattia De Amicis conceived and planned the methodology; Davide Sartirana wrote the paper; Marco Rotiroti, Chiara Zanotti, Tullia Bonomi, and Letizia Fumagalli revised and improved the paper; Davide Sartirana, Marco Rotiroti and Chiara Zanotti worked at the visualization; Mattia De Amicis, Tullia Bonomi, and Letizia Fumagalli supervised the work. All authors have read and agreed to the published version of the manuscript.

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