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Late Quaternary environmental evolution of the Como urban area (Northern Italy): A multidisciplinary tool for risk management and urban planning

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ABSTRACT

The historical center of Como (Northern Italy) is prone to lake flooding and subsidence, due to the presence of unconsolidated silty sediments with poor mechanical properties. The sedimentary basin beneath the town contains over 180 m thickness of Late-Quaternary lacustrine, palustrine and alluvial deposits. The landscape evolution and the present-day environmental setting of the Como area have been reconstructed based on (i) more than 250 core logs and related geotechnical tests, (ii) detailed stratigraphic, sedimentological, paleobotanical and geotechnical analysis of several key boreholes, (iii) multi-year hydrogeological monitoring, (iv) estimation of subsidence rates and (v) integration of geomorphology, archeological findings and historical documents.

Based on our environmental analysis, we derived an integrated geological and geomorphological model of the latest Pleistocene to Holocene local landscape evolution. This model was used to help design an engineering facility to mitigate flood hazards in the Como urban area.

In 2012, we carried out investigations during a re-evaluation of the design parameters for the flood mitigation project at the Como lake-shore. The new campaign included seven boreholes, many in situ and laboratory tests, and four ^{14}C dates. We found an organic silty unit, historical in age, with bad mechanical properties that was critical in the design of the flood mitigation project. We also obtained index properties for static and dynamic conditions, necessary for robust engineering planning. The results were used to update the project and better define future executive phases. Although the importance of acquiring independent experimental data is often overlooked, they can significantly improve the reliability of engineered systems, as demonstrated by the Como town case history.

1. Introduction

The landscape evolution of an area is governed by “extreme” natural events, which can potentially change the geography and stratigraphy of entire regions. Since modern landscapes are very often urban ones, from the societal point of view, geohazards are today among the most serious factors of environmental risk for local industrial installations and large metropolitan areas. Even if much effort has been put into characterizing the causes and dynamics of geohazards, losses are continuously increasing due to a growing population density, which can result in incautious use of the land (e.g., Smith, 2013).

The risk posed by geological hazards seems to be poorly understood, even in the highly industrialized and populated Northern Italy, as illustrated for instance by the “expected” extensive damage to modern industrial buildings during the May–June 2012 seismic sequence in the Po Plain (e.g., Dolce and Di Bucci, 2014; Cimellaro et al., 2014; Michetti et al., 2012), resulting in losses totaling over 13 billion euros (Daniell and Vervaeck, 2012).

Geotechnical failures of anthropic infrastructure are spread worldwide and historical failure cases have deeply shaped the engineering profession (Delatte, 2008). Lessons learnt from such disasters can help in avoiding future failures. Very few disasters occur because of lack of fundamental knowledge or technology: the main reasons for failures are human factors, such as shortcomings in the use of existing geological or geotechnical knowledge and inadequate field monitoring (Sowers, 1993; Bea, 2006). The importance of acquiring independent experimental data during the design stage of an engineering project is often overlooked, even if it applies standard-practice techniques and investment of relatively little money in respect of the total costs. A proper approach enables to identify geohazards possibly occurring during the construction and maintenance of engineering projects (e.g., Xu et al., 2009; Huang et al., 2015).

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This paper illustrates how knowledge of the natural environment and the territorial setting, derived from geological analysis, can be a valuable tool in managing those risks that can affect the integrity and stability of urbanized areas, including their cultural heritage and engineering facilities. In the case of Como, losses might be caused mainly by subsidence and floods.

An engineering geological model derived from stratigraphic, geotechnical and hydrogeological data was developed and tested during the building of a facility in the Como downtown urban area, located in a lake-shore environment prone to subsidence at the northern margin of the Lombardy Po Plain (Fig. 1a). The model provided a suitable general workflow for urban planning and furnished guidance for choosing proper operational techniques. The workflow also highlighted the need for a robust organization and control over construction works, as well as good communication with the public and proper investigation of the delicate interplay of technical and cultural matters in environmental policy (see for instance the discussion in Laborde et al., 2012).

Subsidence phenomena and severe coastal and river floods can be serious threats in urban areas, as illustrated by numerous cases in Italy (e.g., Manunta et al., 2008; Stramondo et al., 2008; Sadori et al., 2014; Comerci et al., 2015 for Rome, and Teatini et al., 2005; Tosi et al., 2013 for Venice) and worldwide (Amelung et al., 1999; Buckley et al., 2003; Fruneau et al., 2005; Fernandez et al., 2009; Galve et al., 2009; Hu et al., 2004; Thierry et al., 2009). The methods adopted here could be applied in similar settings where risks posed by natural and anthropogenic hazards threaten cultural heritage sites. Indeed, the town of Como, like many other cities, has a history spanning millennia and thus it is possible to gather data from not only a geological or geomorphological perspective, but also from archeology and historical chronicles and documents. In particular, archeology and geomorphology in coastal areas can quantify relative topographic movements between the land and the sea or a lake (Gilli et al., 2003; Marriner and Morhange, 2007; Stanley and Toscano, 2009).

Moreover, many lacustrine basins are spread at the foothills of the whole Alpine chain; these areas are highly populated and host relevant economic properties, being located in the heart of Central Europe. In this sense, the case of Como is not dissimilar in respect of many other cities located in lacustrine coastal areas at the piedmont of mountain belts, in Europe and elsewhere.

2. Geological and environmental framework

Lake Como, located at the foothills of the Southern Alps, is λ-shaped and occupies a glacial valley at an elevation of 198 m a.s.l. The Adda River is the main tributary, entering the lake in the northern sector, and is also the only outflow, at the SE termination of the lake.

The town of Como lies at the SW end of the western branch, which is hydrologically closed. A NW–SE oriented alluvial plain of ca. 5 km^2 and gradually rising from the lake level to 220 m a.s.l. at its southern margin, hosts the Como historical downtown. Due to its position and geomorphologic setting, the basin has collected sediment from a drainage area of more than 4500 km^2. The plain is drained by two small water courses, the Cosia and Valduce creeks, which are artificially forced to flow underground at their very end before flowing into the lake.

The town is built on a sedimentary basin containing a thick sequence of post-LGM (Last Glacial Maximum) lacustrine, palustrine and alluvial sediments. The basin is enclosed by two opposite-facing bedrock slopes,

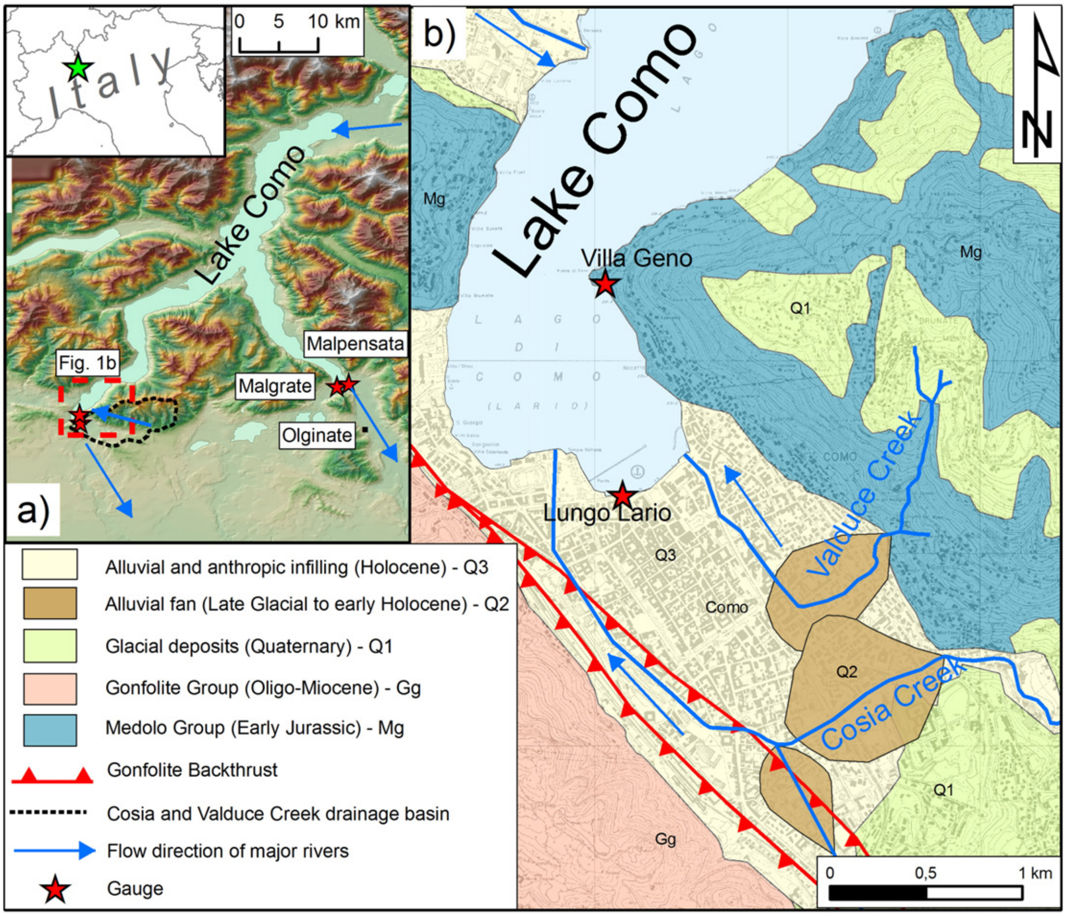

Fig. 1. a) Digital elevation model showing location of Como town, at the southern tip of Lake Como; the map shows also the Cosia and Valduce creeks drainage basin (black dotted line), the position of the hydrometer stations (gauge) and of the *Olginate* dam. Blue arrows indicate the flow direction of major rivers. b) Simplified geologic map of the study area, modified after Ispra (2013).

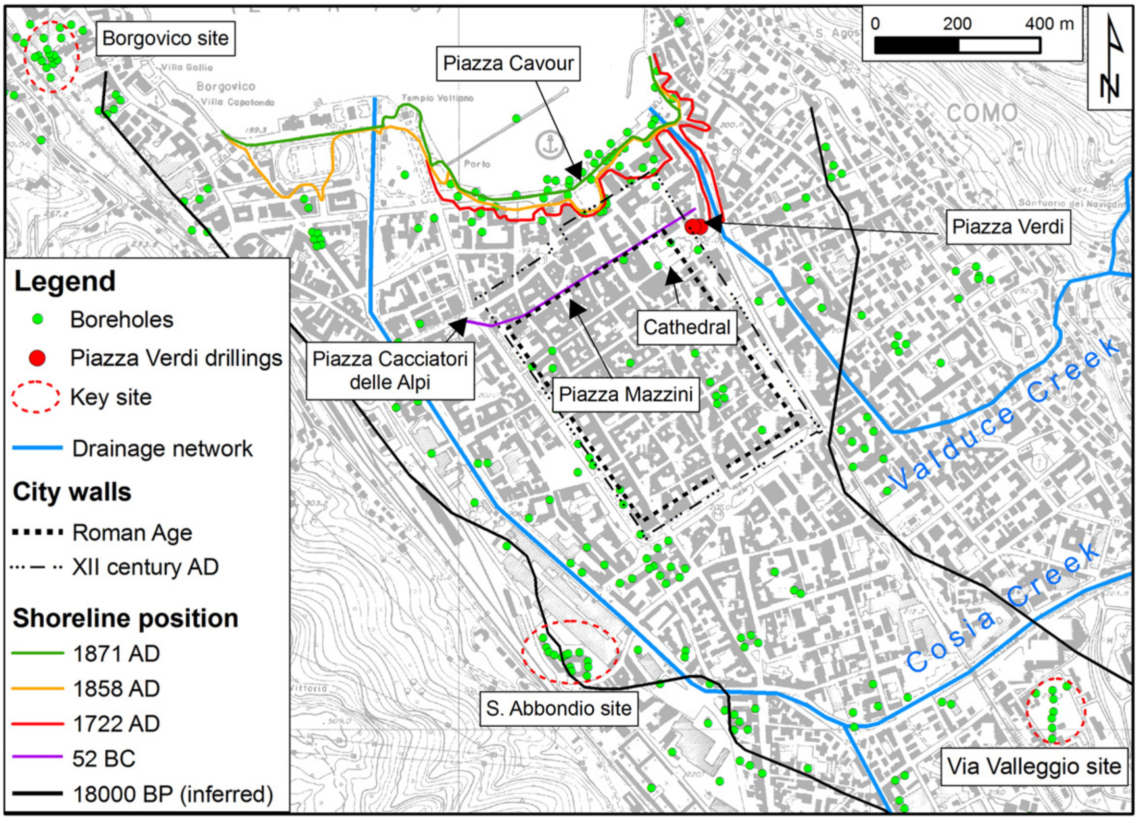

Fig. 2. Map of the Como urban area, based on a topographic map at a 1:10,000 scale (CTR, Carta Tecnica Regionale), showing the available borehole logs, the local drainage network, the reconstruction of the shoreline position at different times and the main archeological and urban features.

composed of Mesozoic pelagic carbonates (Medolo Gr. — Early Jurassic) to the NE, and deep-sea turbiditic conglomerates (Gonfolite Gr. — Oligocene-Miocene) to the SW(Fig. 1b). A review of the regional geological framework is contained in Ispra (2013).

The Como urban area is bordered to the SW by the Gonfolite Backthrust, a major regional N-verging structure, putting the Gonfolite Group in tectonic contact with the underlying Mesozoic pelagic units (e.g., Bernuolli et al., 1989). The recent activity of this structure is indicated by deformed Pliocene-to-Quaternary deposits outcropping near Novazzano and Balerna (Ticino, Switzerland; e.g., Bini et al., 1992; Zanchi et al., 1997; Sileo et al., 2007). An outcrop in the Como urban area ("*Borgovico* site" after Livio et al., 2011) shows evidence of Late

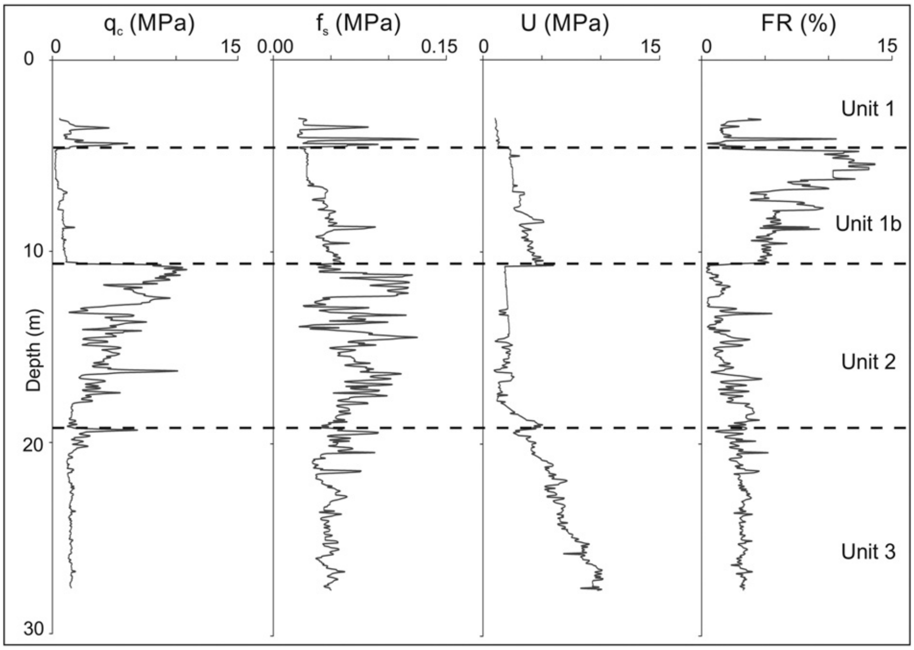

Fig. 3. Result of a standard piezocone test (CPTU4), including measurements of cone resistance (q_c), sleeve friction (f_s), and pore water pressure (U) profiles. The calculated parameter FR (friction ratio) is also reported. Black dotted lines highlight the boundaries between different stratigraphic units; location of the probe is shown in Fig. 6.

Pleistocene-to-Holocene reverse surface faulting along a secondary splay of the Gonfolite Backthrust, thus pointing to the need to consider local seismic potential (e.g., Michetti et al., 2012).

In 1998 the Geology Research Group at Insubria University started a systematic study of the geological, environmental and urban evolution of the Como area. Multidisciplinary data collection (Section 3), encompassing geological disciplines (stratigraphy, hydrogeology, geotechnics), archeology and environmental sciences (^{14}C dating, subsidence monitoring, analysis of biological proxies), have been systematically conducted since then. These observational data allowed us to draw a conceptual model of the Como basin (Section 4). In the last three years, we have tested this model in cooperation with the Como Municipality to mitigate flood hazards (Section 5).

3. Modeling the urban subsurface: multidisciplinary data collection

Land subsidence in the Como area has been studied for more than 40 years. In 1974, a municipal commission was established to study the phenomenon, which was causing severe damage to edifices. The first reconstruction of the Como town stratigraphy was based on direct investigations and the collection of more than 100 borehole logs (Comune di Como, 1980).

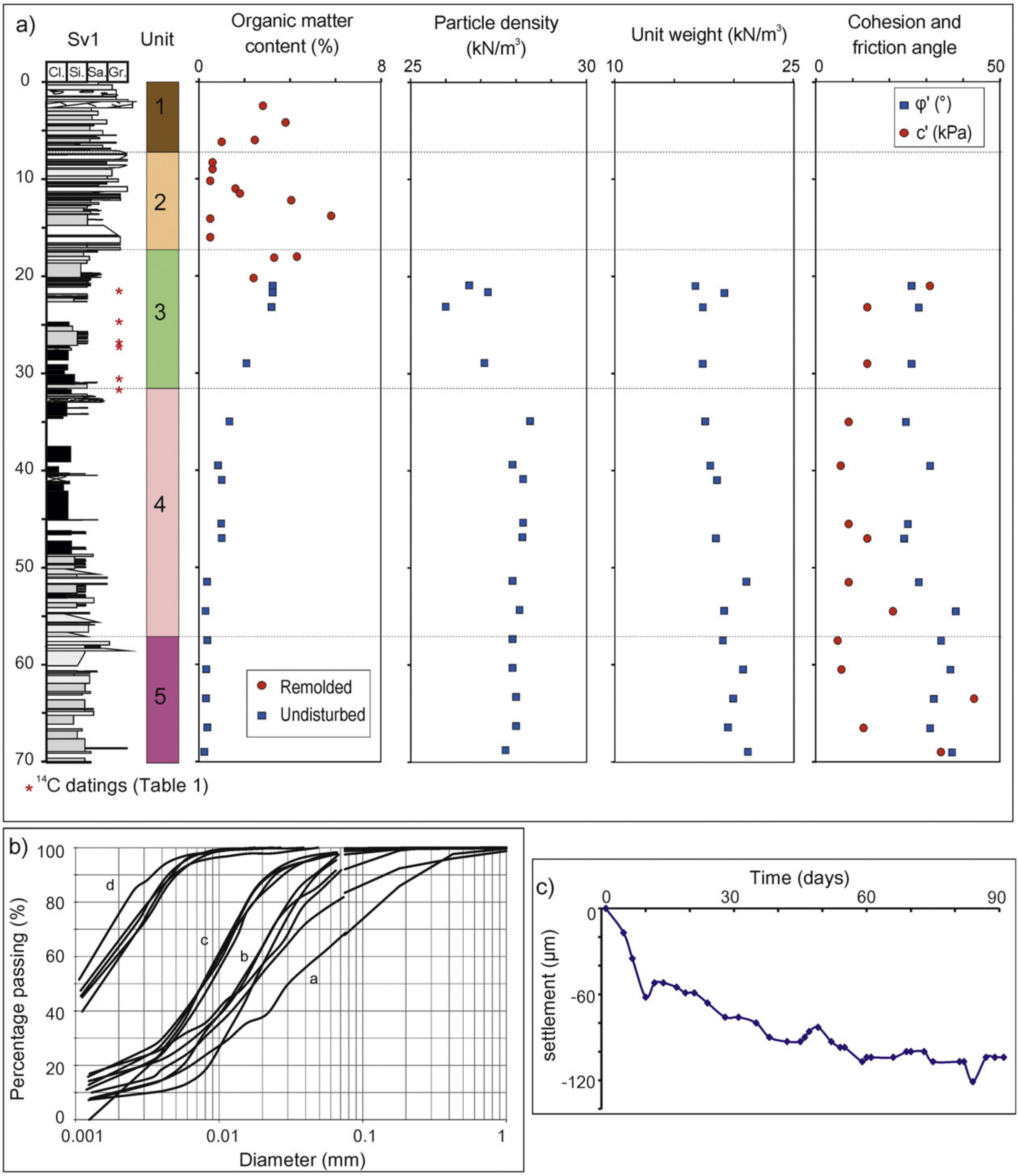

Fig. 4. a) Lithology of sediment core SV1 from *Piazza Verdi* site and related index geotechnical properties. Geotechnical tests (organic matter content, unit weight, particle density, cohesion and friction angle) were carried out at Ispra laboratories; b) grain size distribution: a — samples between 0 and 20 m, b — samples between 21 and 32 m, c — samples between 33 and 49 m, d — samples between 51 and 69 m; c) Time/settlement curve related to a long duration (90 days) oedometer test.

Subsequent research was focused on the geological framework and landscape evolution (Bini, 1987, 1993, 1996; Bini and Castelletti, 1986; Castelletti and Orombelli, 1986), hydrogeological setting (Beretta et al., 1986; Apuani et al., 2000) and archeology (Caniggia, 1968; Luraschi, 1987; Uboldi, 1993).

In recent years, studies by the Insubria University focused on the lacustrine environment and related geohazards (Fanetti and Vezzoli, 2007; Fanetti et al., 2008), active tectonics (Livio et al., 2011) and the post-LGM evolution of the area (Comerci, 2004; Comerci et al., 2007; Capelletti, 2008; Ferrario, 2013; Martinelli, 2014). Most of the information has been integrated in local policy documents (e.g., Comune di Como, 2011).

3.1. Stratigraphy

The sedimentary infill of lake basins records past climatic changes and also extreme past events, as demonstrated by several authors (e.g., in particular for lacustrine settings of the same Alpine region, Fanetti et al., 2008; Lauterbach et al., 2012; Magny et al., 2012; Strasser et al., 2013). The sedimentary basin beneath the town of Como preserves an archive of environmental data that is almost continuous because of the high sedimentation rate and virtually no erosion. However, the sediment architecture shows important lateral and vertical facies changes. The Como urban subsurface is composed of late-glacial and Holocene loose sediments from different depositional environments; only the upper ca. 180 m of the sedimentary sequence has been directly explored by boreholes.

We conducted field surveys at 1:10,000 scale for production of the new official geological map of Italy(Ispra, 2013) and gathered available stratigraphic data from private and public archives. More than 250 borehole logs, covering a territory of 5 km^2 and including the entire urban area were collected. Most of the boreholes were a few tens of meters deep, but ca. 5% of them reach 120 to 180 m depth. Drillings were made between 1950 and 2013 for different purposes, thus the data from the logs are of heterogeneous quality. All data were therefore standardized and georeferenced on a topo map at 1:10,000 scale (Carta Tecnica Regionale — CTR) with meter accuracy (Fig. 2).

The generalized stratigraphic succession of the whole urban area is based on grain-size distribution, organic and archeological content and geotechnical index properties of the sediments. The basic stratigraphy (Comune di Como, 1980) has gradually improved with time, with the adding of more recent data (Comerci et al., 2007; Ferrario, 2013).

Some key sites are highlighted in Fig. 2: the most detailed stratigraphic logs are located at *Piazza Verdi* and near Como Cathedral. At *S. Abbondio*, several boreholes and two ^{14}C dates are available (Castelletti and Orombelli, 1986; Comerci, 2004; Comerci et al., 2007). At *via Valleggio*, direct observation of stratigraphic sections up to 7 m high and 15 m wide was possible and two ^{14}C dates were obtained (Comerci et al., 2007). At *Borgovico*, the Gonfolite Backthrust was observed (Livio et al., 2011).

The sedimentary sequence is composed (from the top) of 1–10 m of heterogeneous reworked material with archeological remains (Unit 1); in the lake-shore area, a silty and highly compressible sub-unit (Unit 1b) has been recognized within the anthropic sediments. Alluvial sands and gravels (Unit 2) are present down to a depth of 15–24 m. Under this sandy gravel unit are up to 30 m of palustrine organic and highly compressible silts (Unit 3); in *Piazza Verdi*, they date between 4 and 18.5 cal kyr BP. At some sites, two distinct facies have been recognized, the first one being more sandy (Unit 3a) and the second one more clayey (Unit 3b). Below 40–60 m depth, distal glaciolacustrine sediments with dropstones are present (Unit 4) and overlie coarser proximal deposits (Unit 5).

3.2. Geotechnical data

3.2.1. Lake-shore area — 1997 campaign

The lake-shore area was investigated in 1997 for a preliminary study for designing the defense system against floods (Comune di Como, 1997). Ten cores were drilled, each one 60 m deep. In situ tests included Standard Penetration Tests (SPT), Lefranc Permeability Tests (LPT) and Cone Penetration Tests with pore pressure measurements (CPTUs). Laboratory analyses were carried out on 88 undisturbed and 9 remolded samples. Inside the drilling holes, 9 piezometers and a magnet extensometer were installed.

Borehole logs were used to calibrate data of 5 CPTU tests, up to 30 m deep. Cone resistance (q_c), sleeve friction (f_s) and pore pressure (U) were recorded at 5 cm intervals; a friction ratio (FR), defined as the percentage ratio between f_s and q_c, was calculated. Sedimentary facies were recognized, based on cone resistance, vertical grading and boundary characteristics (e.g., Amorosi and Marchi, 1999).

Fig. 3 presents the results of test CPTU4 (see Fig. 6 for location), between 3.05 and 27.6 m depth. The investigated sequence represents the most surficial part of the stratigraphy illustrated in Section 3.1. Anthropic fills (Unit 1) show q_c values between 2 and 10 MPa, whereas an FR range of 2–3% is recorded, with a single peak reaching 10%. The stratigraphic succession previously adopted for the urban planning indicated a boundary between coarse anthropic deposits and alluvial sediments. Subsequent research suggested a finer horizon, named Unit 1b, overlying the alluvial deposits of Unit 2. We identify this package because of its peculiar signature on CPTUs, defined by very low q_c values (1–2 MPa) and FR varying between 3 and 12%; the highest FR peaks were recorded in this unit. The upper limit of Unit 1b is characterized by a sharp decrease in q_c and an increase in FR, while its lower limit is highlighted by an abrupt increase in q_c and f_s and a decrease in U and FR values.

Alluvial sediments of Unit 2 show q_c values that are higher (5–15 MPa) and FR that are lower (1–2%) than the other units. A coarsening upward trend is generally recognizable, and wide fluctuations are due

Table 1

^{14}C ages and calibration of samples from the Como urban area. Calibration was carried out applying Oxcal software (https://c14.arch.ox.ac.uk/oxcal/OxCal.html, last accessed April 2014) and the IntCal13-calibration curve (Reimer et al., 2013).

Site	Lab code	Dated material	Type	Unit	Sediment core depth (m)	Elevation (m a.s.l.)	Conventional date (^{14}C yr BP)	2 s calibration (cal. yr BP)	Reference
Piazza Verdi	RC231	Charcoal	AMS	3	21.70–21.95	179.2	3959 ± 61	4779–4183	This paper
Piazza Verdi	LTL2281A	Vegetal remains	AMS	3	25.00–25.20	175.9	4590 ± 55	5467–5052	Capelletti (2008)
Piazza Verdi	LTL2282A	Vegetal remains	AMS	3	30.80–31.00	170.1	12,496 ± 55	15,060–14,305	Capelletti (2008)
Piazza Verdi	GrA-30878	Bulk sediment	TOC	3	31.95	169.05	15,140 ± 70	18,602–18,182	Capelletti (2008)
S. Abbondio		Wood		3	8.74–8.78	201	11,730 ± 180	14,006–13,213	Castelletti and Orombelli (1986)
S. Abbondio	GrA-23357	Wood		3	5.07–5.10	204	13,230 ± 120	16,260–15,500	Comerci (2004)
Via Valleggio	GrA-29158	Organic sed.		3	4.50–4.60	209	5100 ± 50	5940–5725	Comerci et al. (2007)
Via Valleggio	GrA-29436	Organic sed.	AMS	3	5.00	209.5	13,880 ± 200	17,422–16,247	Comerci et al. (2007)
Lake-shore	LTL13422A	Wood	AMS	1b	11.98	186.7	703 ± 40	730–560	This paper (Fig. 12d)
Lake-shore	LTL13423A	Wood	AMS	1b	16.94	181.7	1443 ± 50	1420–1270	This paper (Fig. 12d)
Lake-shore	LTL13424A	Wood	AMS	3	17.47	181.2	6447 ± 45	7431–7278	This paper (Fig. 12d)
Lake-shore	LTL13425B	Wood	AMS	3	38.40	160.3	6570 ± 45	7570–7420	This paper (Fig. 12d)

to local finer horizons. The transition to the lowermost Unit 3 is gradational and marked by a decrease in q_c and an increase in U values. The q_c range is 2–3 MPa and the FR ranges from 1 to 6%; the unit is quite uniform, but locally a much more heterogeneous deposit related to a rhythmic alternation of organic and inorganic strata is present, as confirmed by borehole logs.

3.2.2. Piazza Verdi drillings

Two drillings for scientific analyses (SV1 and SV2, 65 and 70 m deep, respectively) were carried out at *Piazza Verdi*(Fig. 2) in 2005. Sedimentological, paleomagnetic, geochemical, geophysical and paleobotanical (pollen and plant macrofossils) analyses, added to ^{14}C-AMS dating, allowed calibration of the subsurface database and placement of this site within the regional framework of the southern Alps.

Here we describe the geotechnical results obtained at *Piazza Verdi* on SV1 (tests carried out at ISPRA laboratories), while details on geochemistry and biological proxies acquired from SV2 will be the subject of a companion paper.

A number of parameters were investigated (Fig. 4a). As soon as the sediments were collected, pocket penetrometer and shear values were recorded; resistance gradually increases from 50–150 kPa between 6 and 50 m depth to 200–300 kPa below 50 m. Inside the drilling holes, 11 standard penetration tests (ASTM D 1586) were performed. N_{spt} values range between 3 and 12 for Units 1 and 2, whereas maximum

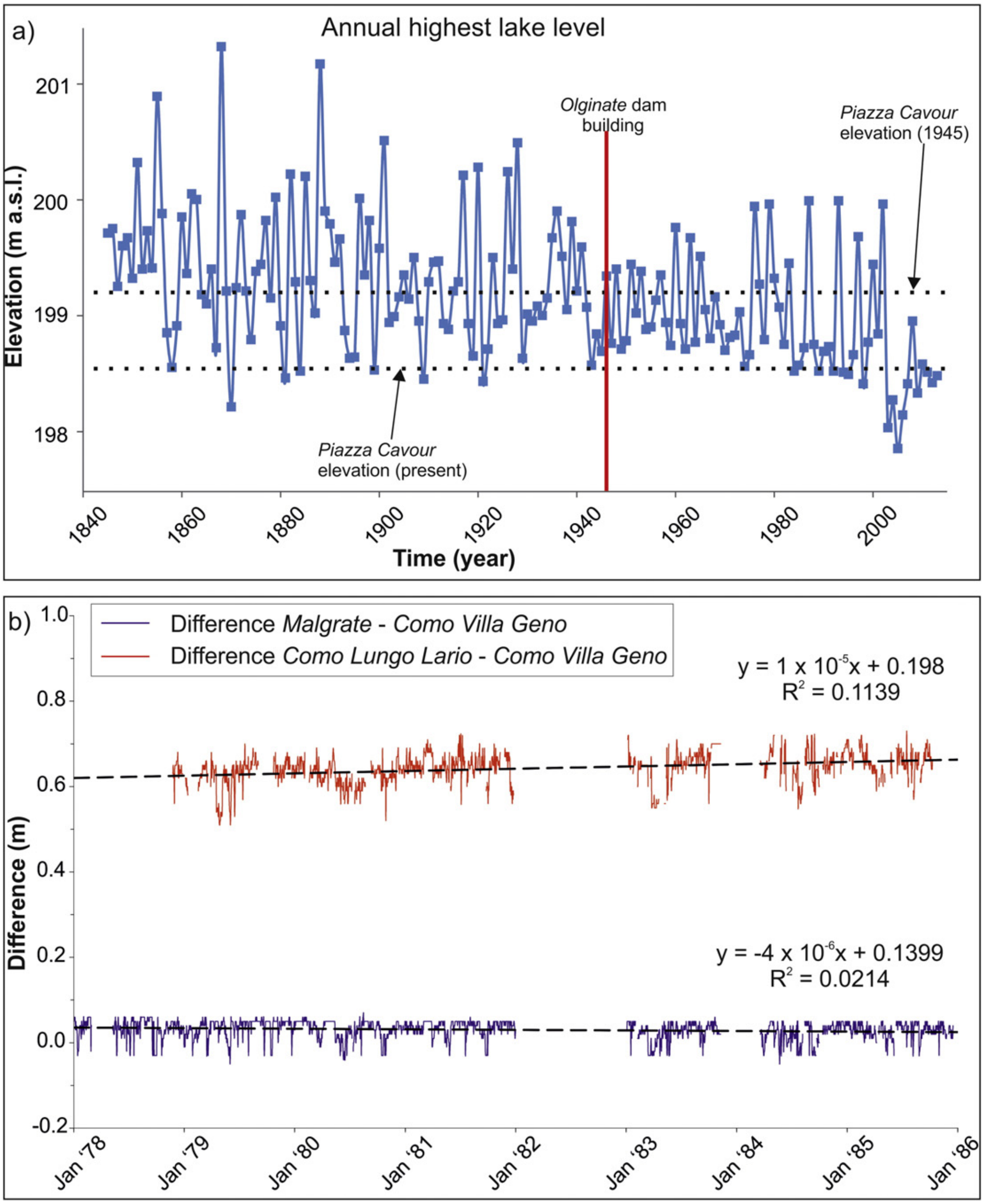

Fig. 5. a) Annual highest lake-level recorded in the Lecco branch during 1845–2013 (1845–1935: *Malpensata* gauge; 1936–2007: *Malgrate* gauge, Moisello and Vullo, 2010; 2008–2013: *Malgrate* gauge, data courtesy Consorzio dell'Adda). Dotted lines represent *Piazza Cavour* elevation in 1945 (199.18 m a.s.l.) and today (198.53 m a.s.l.); the vertical red line indicates the building of *Olginate* dam (see Fig. 1a). b) Lake levels daily recorded during 1977–1987 in the three measurement points; note the difference between *Malgrate* and *Villa Geno* (blue series) and between *Lungo Lario* and *Villa Geno* (red series); the first one has a horizontal trend, indicating the relative stability of the two locations; the difference between *Lungo Lario* and *Villa Geno* is increasing because *Lungo Lario* measurements do not reflect the real lake-level, but are equal to the lake-level plus the intervening ground subsidence; see Fig. 1 for gauge location.

values of 39 were recorded for Unit 5. Undrained shear resistance was measured with 13 Vane-borer tests (ASTM D 2573), resulting in values of 65–110 kPa.

Geotechnical laboratory tests were carried out on 15 undisturbed samples collected from depths of 20 m to 70 m and on 80 disturbed samples collected from the more surficial layers.

The grain-size distribution, determined from a sieving and sedimentation procedure based on ASTM D 422 (Fig. 4b), the particle density and, for clayey samples, plastic and liquid limits, were measured throughout the stratigraphic column. In the first 20 m below the surface the material is predominantly detrital, with numerous anthropogenic lithics. Between 20 and 69 m the following particle size classes were identified: silts with clay between 21 and 32 m (Unit 3); clays with silt between 33 and 49 m (Unit 4); silts with clay and locally sand between 51 and 69 m (Units 4 and 5).

The organic content, measured according to ASTM D 2974, is highly variable in Units 1 and 2; values are particularly high around 20 m depth (3%; Unit 3), then decrease to 1% between 40 and 50 m (Unit 4), reaching finally 0.3% below 50 m (Unit 5; Fig. 4a).

The particle density shows two different trends: above the depth of 30 m, values fluctuate from 26 to 27.2 kN/m^3, presumably due to lithological inhomogeneity. Below that depth, values are much more constant, around 28 ± 0.2 kN/m^3.

The investigated sediments all show a saturation close to 100%; the unit weight in saturated condition measured in undisturbed samples is between 17 and 19 kN/m^3 down to a depth of 50 m, and between 19 and 21 kN/m^3 at depths greater than 50 m (Fig. 4a). The samples belonging to Unit 5, show higher unit weight and lower void ratio, depending on the increasing lithostatic load with depth.

Cohesion and friction angle were derived from a series of triaxial tests: cohesion generally varied between 5 and 15 kPa, although higher values were recorded locally. The friction angle ranges between 24° and 28° in the upper part of the sequence, whereas below 50 m depth values were 30° to 40°.

A series of 16 oedometer tests was carried out using the Casagrande procedure (ASTM D 2435) to evaluate the preconsolidation pressure. A few tests performed on samples cored near the lake-shore in the first 20 m show a moderate over-consolidation. *Piazza Verdi* samples show that from 20 to 35 m depth the over-consolidation ratio reduces and reaches the values of normal consolidation, characteristic of soils still consolidating under their own weight. Two different interpretations can be suggested: (i) the sediments were not loaded by the glacier because they settled after its retreat; (ii) the sediments settled in the presence of a melting glacier, but the pressure was totally or partially absorbed by a water layer below the ice.

In order to evaluate long-term compressibility, a long-duration oedometer test was carried out, applying a load of 400 kPa for about 90 days (Fig. 4c). In such a test, the deformation is due to the viscous strain of the solid skeleton and it occurs under a constant effective pressure, and thus also (but not only) when the primary consolidation is ended. The secondary compression index (C_α) value is equal to 0.0027, which is rather low, although between ordinary limits in normally consolidated deposit. Long-duration deformability and viscous phenomena can be, therefore, a cause of subsidence in this area.

Geotechnical results were consistent with each other and highlighted a sharp discontinuity in the stratigraphy at ca. 30–33 m depth, broadly corresponding to the lithological boundary between Units 3 and 4; this fact was related to the environmental evolution of the Como basin, as discussed in Section 4.2.

3.3. Chronological constraint: ^{14}C dates and archeology

A number of ^{14}C dates (Table 1), integrated with the stratigraphic and archeological record, provide time constraints on the post-LGM evolution of the study area. Unit 3 settled out during several millennia since ca. 18.5 cal kyr BP, the minimum age for the deglaciation of the basin. The oldest archeological finds (from the Iron Age) were found

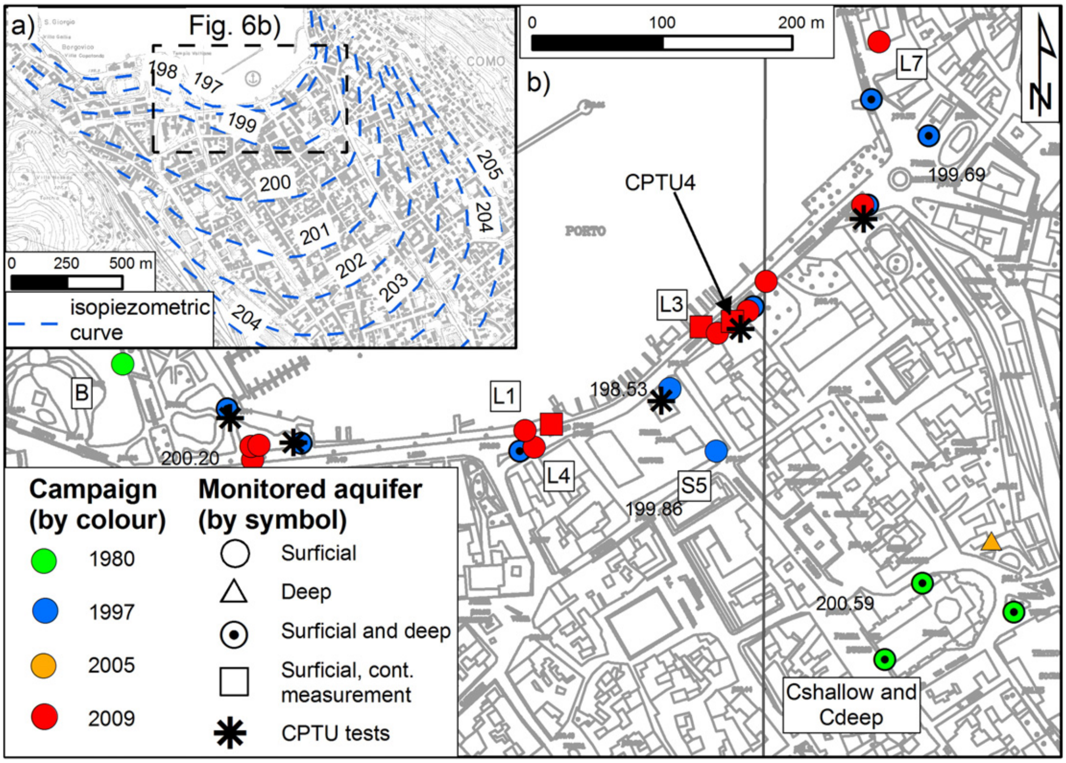

Fig. 6. a) Schematic reconstruction of curves of equal piezometric level of the phreatic aquifer (values expressed in m a.s.l.). b) Location of the instrumental network for groundwater monitoring and of CPTU tests.

on the mountain slopes surrounding the basin (Uboldi, 1993); at that time, the plain was an unhealthy, marshy area, frequently affected by debris flows and floods.

An impressive reorganization of the drainage network and related mountain catchment, including the diversion of the Cosia and Valduce creeks in the Como plain, took place immediately before *Novum Comum* was founded in 59 BC (ca. 2000 BP) under the Roman Consul Gaius Julius Caesar. Cosia stream was forced to flow at the base of the SW mountain slope, and Valduce stream on the opposite side, thus allowing the building of the town itself in the center of the plain. To the north, the town was naturally protected by the lake, whereas on the other three sides, town walls were built (Caniggia, 1968; Luraschi, 1987). Archeological evidence found at different sites indicates the migration of the coast and the town harbor towards the north. Among other findings, a Roman quay was discovered in *Piazza Cacciatori delle Alpi*(Jorio, 2004), and in *Piazza Mazzini* wooden remains were found (location in Fig. 2). The present-day*Piazza Cavour* was the dock of the town till 1870.

3.4. Lake flooding and subsidence

The hydrological regime of Lake Como has been regulated since 1946 by a dam located in *Olginate* (see Fig. 1a). The close relation between lake-level control, flooding and subsidence is clearly illustrated in Fig. 5a, where the annual highest lake levels recorded in the Lecco branch during 1845–2013 are shown (Moisello and Vullo, 2010). Lake-level regulation reduces but does not eliminate the flood hazard: in the last decades, major floods occurred in 1987, 1993 and 2002, and the last event of moderate intensity happened in July, 2008.

Most of the archeological finds and also building foundations in the town of Como are presently below groundwater level, thus suggesting significant variations in ground surface and groundwater level in the last centuries. This could be consistent both with ground subsidence and/or groundwater rise related to an increase in lake-level. In the whole Lake Como area, except the town of Como, Roman and Medieval settlements are always above lake-level(Luraschi, 2002), thus suggesting the absence of any significant rise in lake-level in the last two

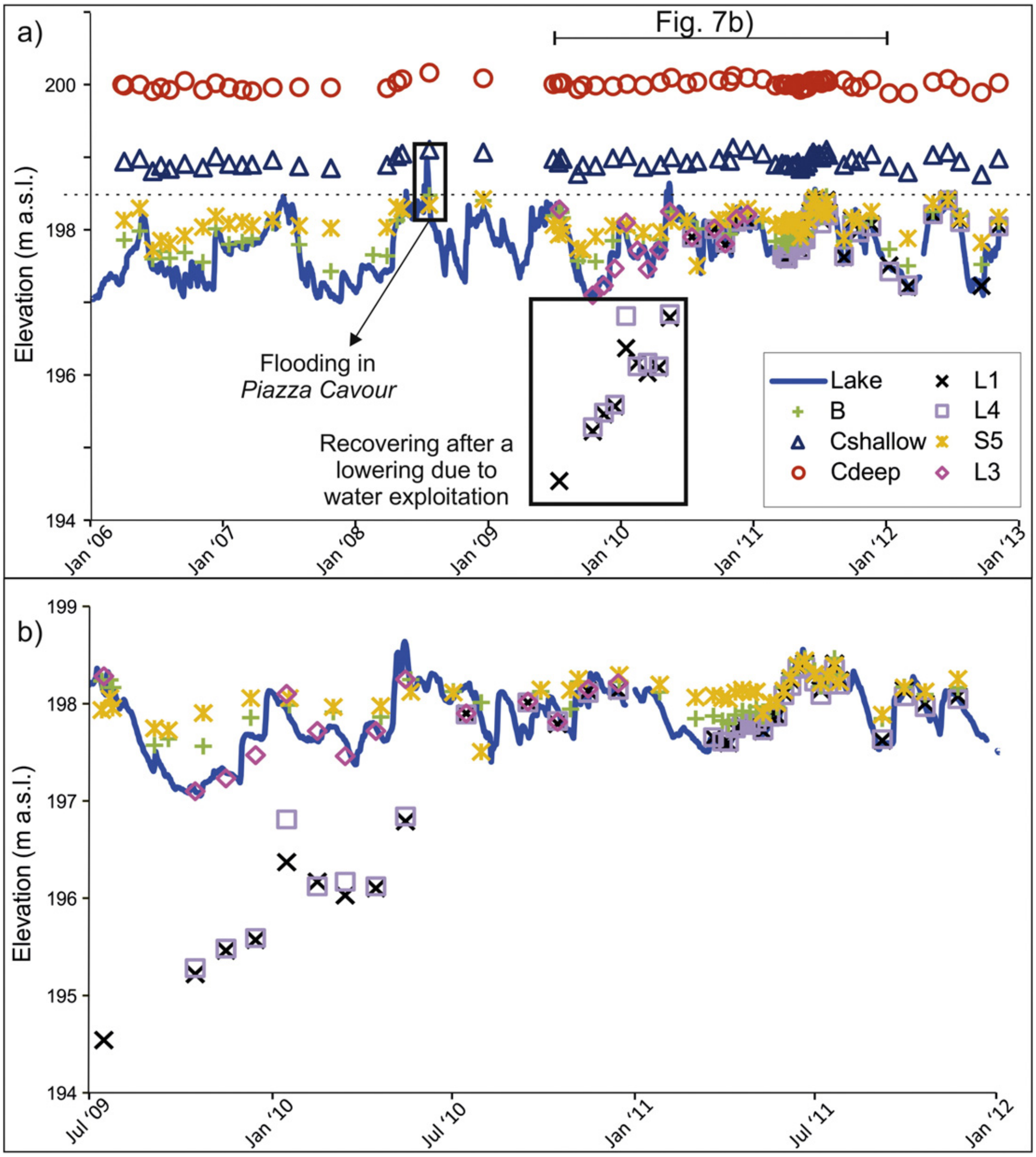

Fig. 7. a) Comparison between lake-level (*Malgrate* station; Fig. 1a) and groundwater level detected at seven selected measurement points (see Fig. 6b) during January 2006–December 2012. L series is located on the lake-shore, S5 at *Piazza Cavour* and C near the cathedral; all instruments excepted C_{deep} refer to the shallow aquifer. The dashed horizontal line represents the elevation at which *Piazza Cavour* is inundated (198.53 m a.s.l.). b) Focus on the coastal area, where engineering works caused a lowering of the water table.

millennia. On the contrary, data in the Como area points to a strong subsidence, driven by local factors. Indeed, the sedimentary basin is characterized by a sequence of young unconsolidated silty sediments with poor mechanical properties, locally more than 30 m thick. These deposits naturally undergo differential settlement due to a decrease in the void ratio, biochemical degradation and decomposition of organic matter.

The zones experiencing higher subsidence rates are also the most valuable areas in terms of cultural heritage and local economy, namely the town's historic center and the waterfront area; thus, even if the subsiding area is spatially limited, the effects are critical to the whole town. Beyond the negative effects on the road network, tourism and the city's image, subsidence also is a significant safety and economic problem.

Surface deformation has been detected by leveling, remote sensing and gauges measurements, and archeological and geological constraints. We can discriminate between natural and anthropogenic components and quantitatively estimate subsidence rates. Here, we build on and expand previous results (Comerci, 2004; Comerci et al., 2007) with new ones and present a new estimate of the 1977–1987 subsidence rate.

3.4.1. Long-term subsidence rates

The boundary between Unit 3 and Unit 4 was used as a marker horizon to estimate the long-term, average subsidence rate since the late-glacial period. This limit, clearly recognizable from stratigraphic logs, is located at approximately 50 m depth near the lake, while it nearly outcrops along the inland borders of the plain, such as at the *S. Abbondio* site. Since Unit 3 does not show any vertical change of facies, the present-day stratigraphic architecture is likely due to subsidence. The limit has been dated at ca. 18.5 cal kyr BP, indicating an average subsidence rate of ca. 2.5 mm/yr in the lake-shore area (Comerci et al., 2007). Subsidence rates decrease to the south and towards the borders of the basin.

Archeological data indicate an average subsidence rate of ca. 1 mm/yr in the last two millennia, which is consistent with the long-term rate (Comerci et al., 2007).

3.4.2. Short-term subsidence rates

Recent subsidence rates were independently estimated from leveling, hydrometric levels and remote sensing. During the period between 1928 and 2012, ten leveling surveys were conducted; the highest rates of subsidence, up to over 20 mm/yr, were recorded during 1950–1975. Groundwater pumping from a deep aquifer was the main cause, but other potential causes include land reclamation, ground overloading and road traffic (Comune di Como, 1980). After that period, subsidence decreased because of the suspension of aquifer exploitation in the Como valley; between 1980 and 1997 there was even a slight increase in elevation of several benchmarks.

Ground sinking can be estimated from hydrometric data, comparing instrumental values of gauges located on stable bedrock and others located on compressible sediments. Three measurement devices are considered here. The gauge located in *Malgrate* (Lecco branch, SE end of Lake Como, see Fig. 1a) gives the “official” lake level and is the one

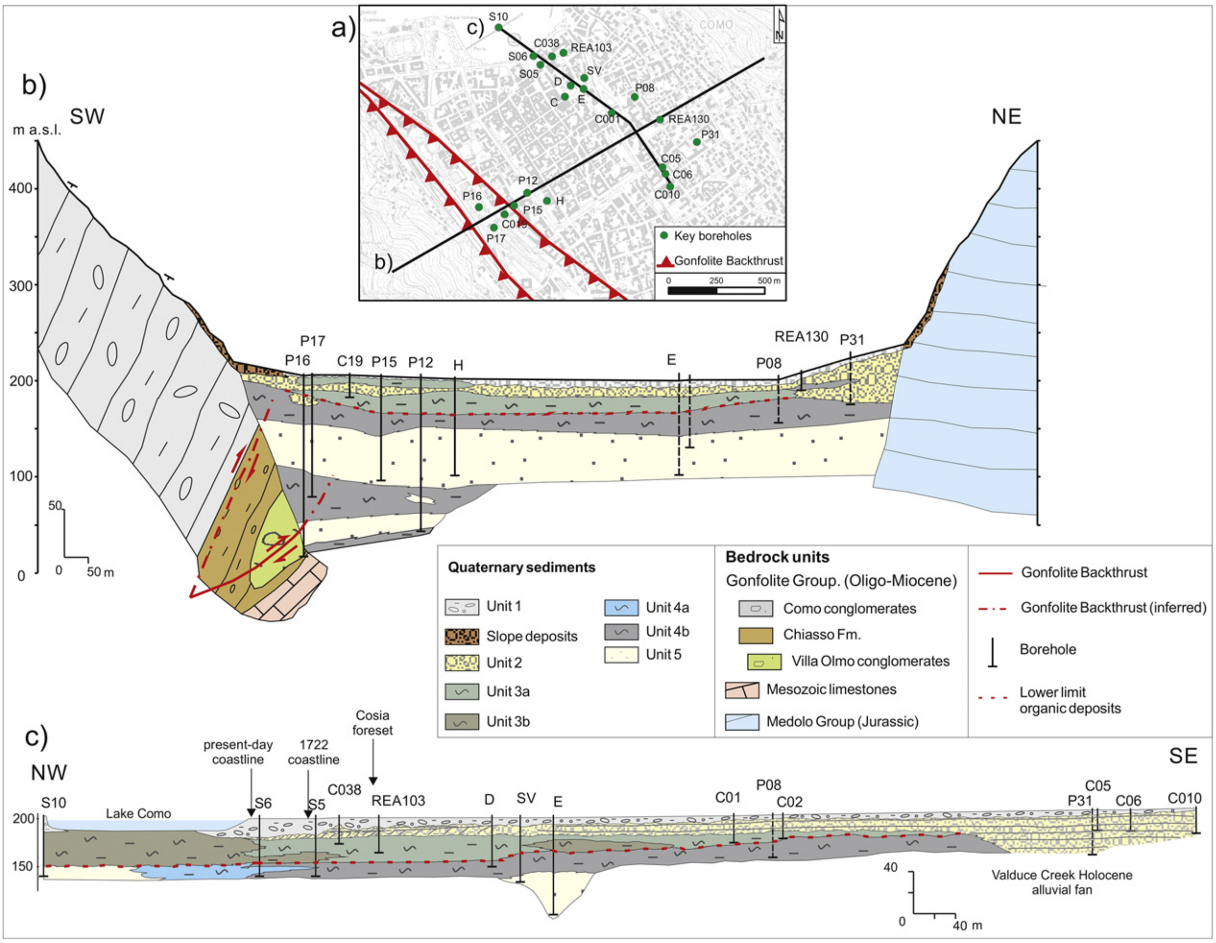

Fig. 8. a) Trace of the sections and position of the stratigraphic logs. b) Geological cross-section SW–NE oriented, perpendicular to the sedimentary basin; vertical exaggeration 2×. c) Section NW–SE oriented, from Lake Como towards the town.
Sections redrawn after Ferrario (2013).

used by institutions responsible for lake-level management. In the Como branch (SW end of Lake Como) two gauges are present, one founded directly on bedrock northeast of Como town (*Villa Geno*, see Fig. 1a/b), and the other is located on the lake-shore deposits (*Lungo Lario*, see Fig. 1a/b). The first two instruments were built in 1936 on stable rock, whereas the latter is located on very young (ca. 120-yr old) highly compressible sediments.

A subsidence rate of 10^{-5} m/day (ca. 3.65 mm/yr) has been calculated; this is an order-of-magnitude value and is consistent with rates estimated with other methods. Data demonstrate the relative stability between *Villa Geno* and *Malgrate* and the progressive lowering of the instrument located at *Lungo Lario*.

During the last 20 years, ground movements have been surveyed both by geodetic leveling (Giussani, 1997; Bonci et al., 2004; Barzaghi et al., 2011) and radar persistent scatterer interferometry PSInSAR (Ferretti et al., 2000). Analysis of ERS2 data (for the 1992–2003 time interval) shows that results are in good agreement (Comerci, 2004). In the absence of external triggering factors, the present-day subsidence rate is comparable to the long-term one, i.e., on the order of a few mm/yr near the lake-shore. In contrast, an uplift trend of up to 2 mm/yr is recorded on the higher relief areas that border the plain, consistent with the regional uplift characterizing the whole pre-Alpine chain (Arca and Beretta, 1985).

Since 2008, relevant engineering works have been carried out on the lake-shore area. Interferometric data acquired for the 2003–2012 period (TRE Europa, 2012) show a cumulative sinking of 4 cm (ca. 5 mm/yr) in the working area, most of which occurred between 2008 and 2009. In contrast, elsewhere in the town a constant rate of 1–2 mm/yr of sinking was recorded.

3.5. Hydrogeology

In the Como urban area, a shallow aquifer is present down to ca. 25 m depth, within anthropic and alluvial deposits (Units 1 and 2); a deeper aquifer, subdivided into several lenses or layers due to lateral heterogeneity, is located in the proximal glaciolacustrine deposits (Unit 5). The confining unit is the sequence of clays and silts of Units 3 and 4 (Beretta et al., 1986; Apuani et al., 2000). The deep aquifer was intensively exploited for civil and industrial supply until 1980, when water extraction was forbidden (Comune di Como, 1980).

Fig. 6a shows the isopiezometric curves related to the mean level of the surficial aquifer in the absence of human-induced alterations: groundwater flows from SE to NW, towards the lake, which is the local base level. This interpretation is derived from multi-year monitoring of the urban instrumental network (Fig. 6b), which consists of ca. 30 piezometers in total, 18 of which are located in the center of the town (Comune di Como, 1997; RCR, 2010). The first systematic measurements were made in 1975–1977, whereas during 1980–2005 only sparse readings were taken; since 2006, monthly measurements have been taken by the Insubria University.

Fig. 7a shows a comparison between lake and groundwater level, for seven selected measurement points, during January 2006–December 2012. All instruments excepted C_{deep} are in the shallow aquifer — the L series is located at the lake-shore, S5 at *Piazza Cavour* and C near the cathedral. The piezometric level in the shallow aquifer near the lake is closely related to the lake-level, and strongly follows its trend, although with fewer high-frequency oscillations and with a short delay. *Piazza Cavour* was partially inundated in July, 2008 (Fig. 7a). Inland, farther

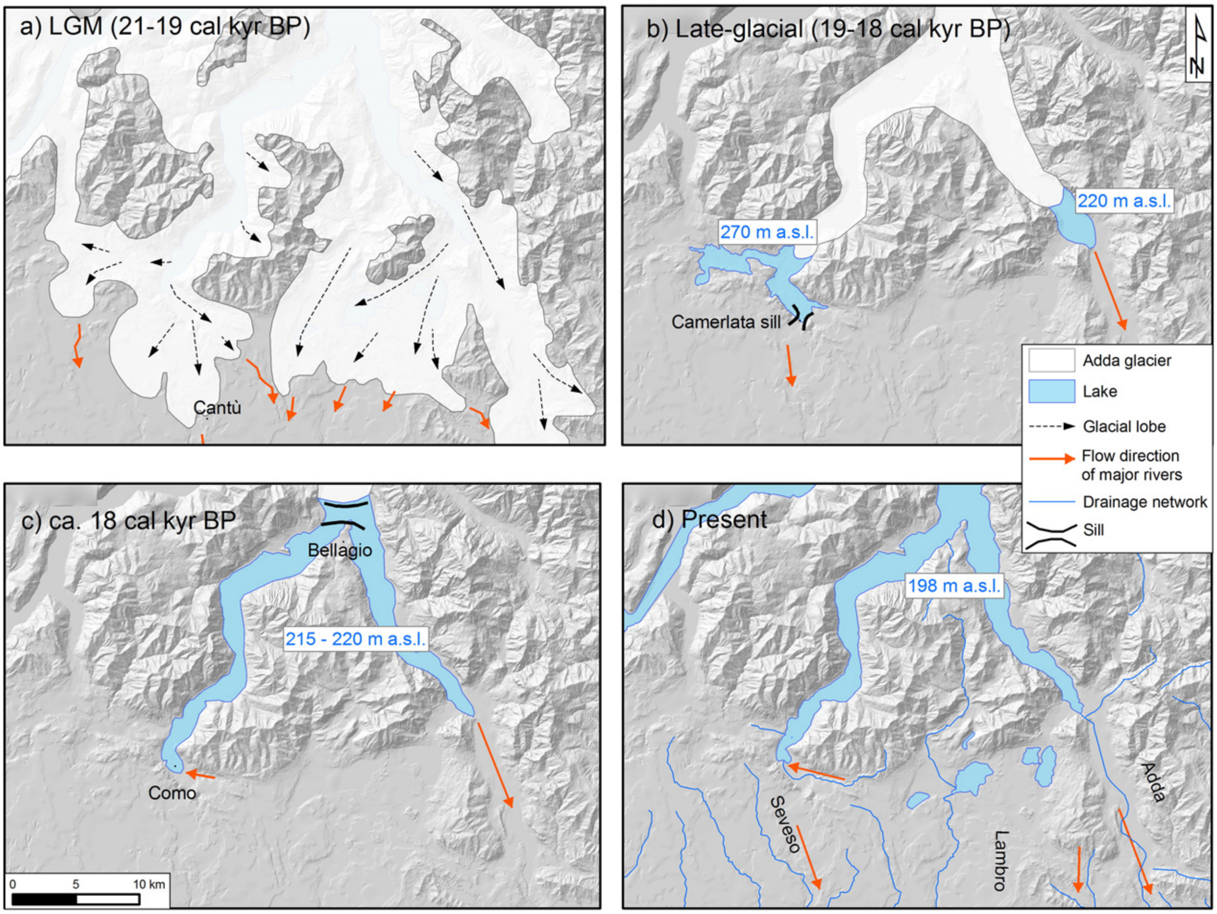

Fig. 9. Simplified landscape evolution of the Como basin since LGM (a), Late-glacial (b), 18 cal kyr BP (c) up to present (d); glacial cover, proglacial lakes and the main drainage system are shown (modified after Bini, 1993).

from the lake, the lake-level influence is less pronounced and variability decreases.

In natural conditions, seasonal variability ranges between 1 and 1.5 m; however, human activities can significantly lower the water level, as happened between June 2009 and June 2010 due to the ongoing engineering works. A lowering of 3–4 m and the subsequent recovery of groundwater level are clearly evident (Fig. 7b).

The few measurement points in the deep aquifer are flowing artesian wells, except for the piezometer named C_{deep}, located just in front of the cathedral together with $C_{shallow}$(Fig. 6b). $C_{shallow}$ has a screen depth at 5 m below the ground surface, and C_{deep} at 21 m. The level in $C_{shallow}$ is always ca. 1 m lower than the one in C_{deep} and thus the wells are definitely monitoring two distinct water bodies — the shallow aquifer for $C_{shallow}$ and a deeper aquifer for C_{deep}. A geochemical investigation is currently underway to better understand the hydrogeological setting of the area.

4. Modeling the urban subsurface: results

Safe urban planning has to be based on the forecast of sediment behavior under stresses (overloading, possible ground shaking, etc.). For Como, this issue is not trivial, because the present-day landscape surrounding the town is the product of many different geologic processes. Firstly, we correlate stratigraphic data in order to draw two geological cross-sections(Section 4.1) and subsequently we reconstruct the landscape evolution since late-glacial times (Section 4.2).

4.1. Stratigraphic correlations

Two cross-sections(Fig. 8a), nearly perpendicular to each other, were drawn based on borehole logs and geotechnical data; stratigraphic units were defined based on those of Section 3.1 but some adjustments were made to take local features into account. Unit 1b is found only in the lake-shore area and not elsewhere; while slope deposits are common on the borders of the plain, thus a specific unit was added.

Fig. 8b shows a SW–NE oriented section, broadly perpendicular to the axis of the sedimentary basin. The section is based on 11 stratigraphic logs, some more than 130 m long (P12, P16, P17), but their stratigraphic detail is low. In this section, only the main units have been recognized, without distinguishing different facies. Well data highlight that the basin, repeatedly occupied by a huge glacier during the Quaternary, is a valley overdeepened by glacial erosion, like many others both on the northern and southern side of the Alps (e.g., Preusser et al., 2010). On the western side of the basin, well P16 reaches the bedrock (Gonfolite Gr.) at 181 m below ground surface (ca. 35 m a.s.l.); bedrock absolute elevation rises to ca. 200 m a.s.l. a few km to the south (Comune di Como, 2011), along the axis of the former ice tongue, thus implying a rise in the valley floor of more than 150 m. Valley sides are characterized by a dip of ca. 45°; a significant increase in dip is recorded in the buried sectors, where it has been estimated at ca. 60°. The increase of valley side dip can be explained, besides selective erosion of less resistant lithologies, as possibly due to structural control from recent activity of the Gonfolite Backthrust.

Fig. 8c shows a NW–SE oriented profile, from the lake towards Como town. The section is based on 15 highly detailed stratigraphic logs and highlights the different lake coastline positions and a Cosia Creek foreset located between the lake-shore and the cathedral (Bini and Castelletti, 1986). The southern part of the section crosses an old alluvial fan attributed to Valduce Creek (Bini, 1993).

4.2. Landscape evolution

4.2.1. Late-glacial

During the LGM, in the Alps dated at ca. 21–19 cal kyr BP (e.g., Ivy-Ochs et al., 2006; Ravazzi et al., 2007), the top of the Adda

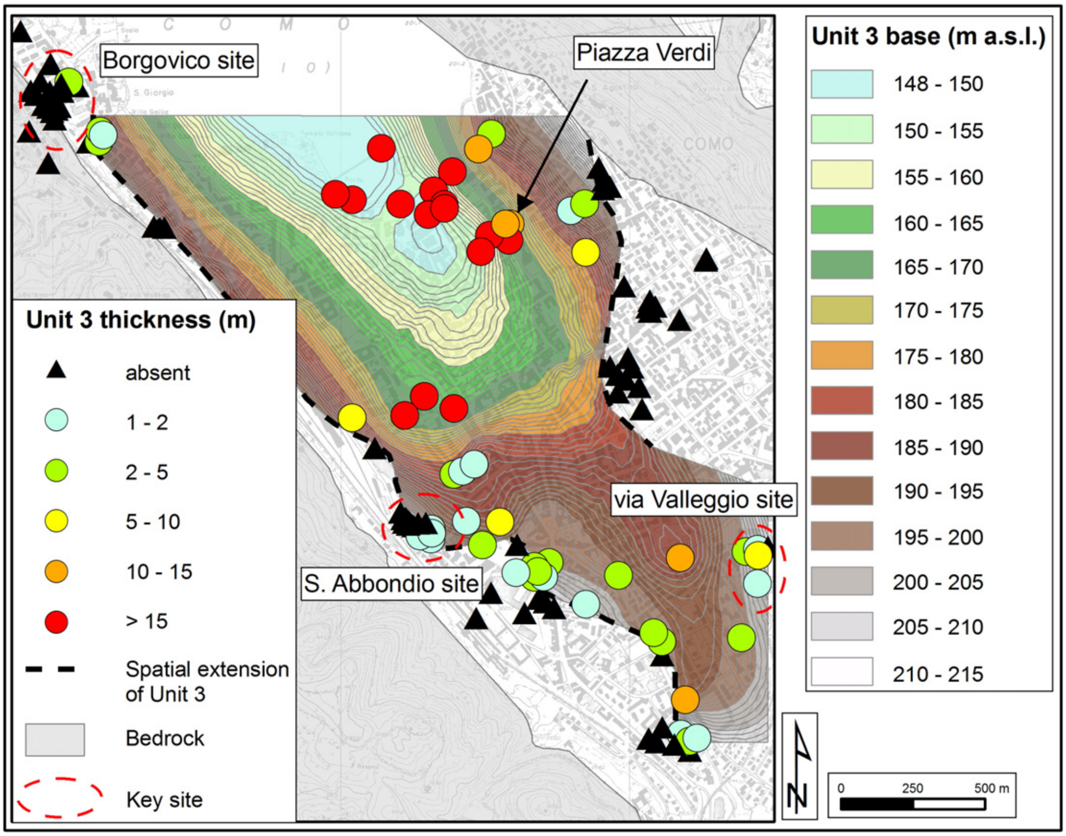

Fig. 10. Thickness of Unit 3 (round symbols) and elevation of Unit 3 base.

Glacier reached about 825 m of elevation on the mountain slopes around Como and spread in the piedmont area as far as the town of Cantù, ca. 10 km south of Como (Fig. 9a). Basin deglaciation of several overdeepened foreland piedmont lakes on southern and northern sides of the Alps, including Lake Como, appears to be synchronous at millennial scale (Ravazzi et al., 2014).

With glacier retreat, a proglacial lake formed at 270 m a.s.l. between the glacier front and the *Camerlata* sill (Fig. 9b) when the *Camerlata* threshold acted as a spillway, and waters flowed to the south in the present-day Seveso River valley. Another proglacial lake was present at the end of the Lecco branch, at an elevation of ca. 220 m a.s.l. (Nangeroni, 1972). During this phase, coarse proximal sediments (Unit 5) and finer deposits with dropstones (Unit 4) settled in the Como plain, suggesting the presence of a relatively wide and deep glaciolacustrine basin and a cold and arid climate.

When glacier retreat reached the Bellagio sill, the local lake-level dropped from 270 to 220 m a.s.l. (Bini, 1993), and the Como branch joined the Lecco branch, generating the modern Lake Como. The Como branch became a closed basin, a sediment trap with a spillway located in the Lecco branch (Fig. 9c). The drainage network around Como town underwent a complete inversion, flowing north now towards the newly born lake.

With the inception of a more temperate and humid climate, organic remains started to be deposited in the lake, locally consisting of marshes and surrounded by vegetated slopes. We dated the first appearance of organic matter in the stratigraphic sequence at several sites; at the *Piazza Verdi* and *via Valleggio* sites ages of ca. 18.5 and 17 cal kyr BP were obtained, respectively (Table 1). At that time, the entire Como plain was deglaciated.

The stratigraphic database was examined using spatial analysis GIS functions. Unit 3 was divided into six classes of different thicknesses (see Fig. 10; 0 m; 1–2 m; 3–5 m; 6–10 m; 11–15 m; >15 m) and plotted on the topographic map. A maximum thickness (>30 m) was found in the lake-shore area and gradually decreased towards the borders of the basin. The elevation field of the base of Unit 3 was calculated by means of a kriging interpolator; this boundary is well-documented by core logs, geophysical and geotechnical parameters, and by biological proxies. This paleo-surface is dated at ca. 18.5 cal kyr BP and its 3D architecture is clearly deformed by the long-term subsidence (Fig. 10).

Unit 3 did not cover the whole Como urban area: in the outer part of the basin (e.g., *Borgovico* site) Unit 2 directly overlies Unit 4. The spatial extension of Holocene organic silts runs at an elevation of ca. 215–220 m a.s.l., which we interpreted as the paleo-lake level when the two branches of Como and Lecco were connected due to deglaciation and organic material started to accumulate on the lake bottom. We suggest that while on higher areas (*Borgovico*) a subaerial environment developed, on peripheral areas (e.g., *S. Abbondio*) a shore environment was present, and the inner part of the basin (e.g., *via Valleggio*) was occupied by shallow waters (Comerci et al., 2007). By that time, the glacier had retreated north of the Bellagio sill, otherwise the lake-level would have been at 270 m a.s.l.

4.2.2. Post-glacial to Holocene

The sedimentation of Unit 3 in the center of the Como basin continued up to Early Holocene in a stable lacustrine environment, with no glacial influence. The supply of coarse material was very low, because the local drainage network consisted of small tributaries. Only along the edge of the plain did slope and fan deposits contribute to the filling

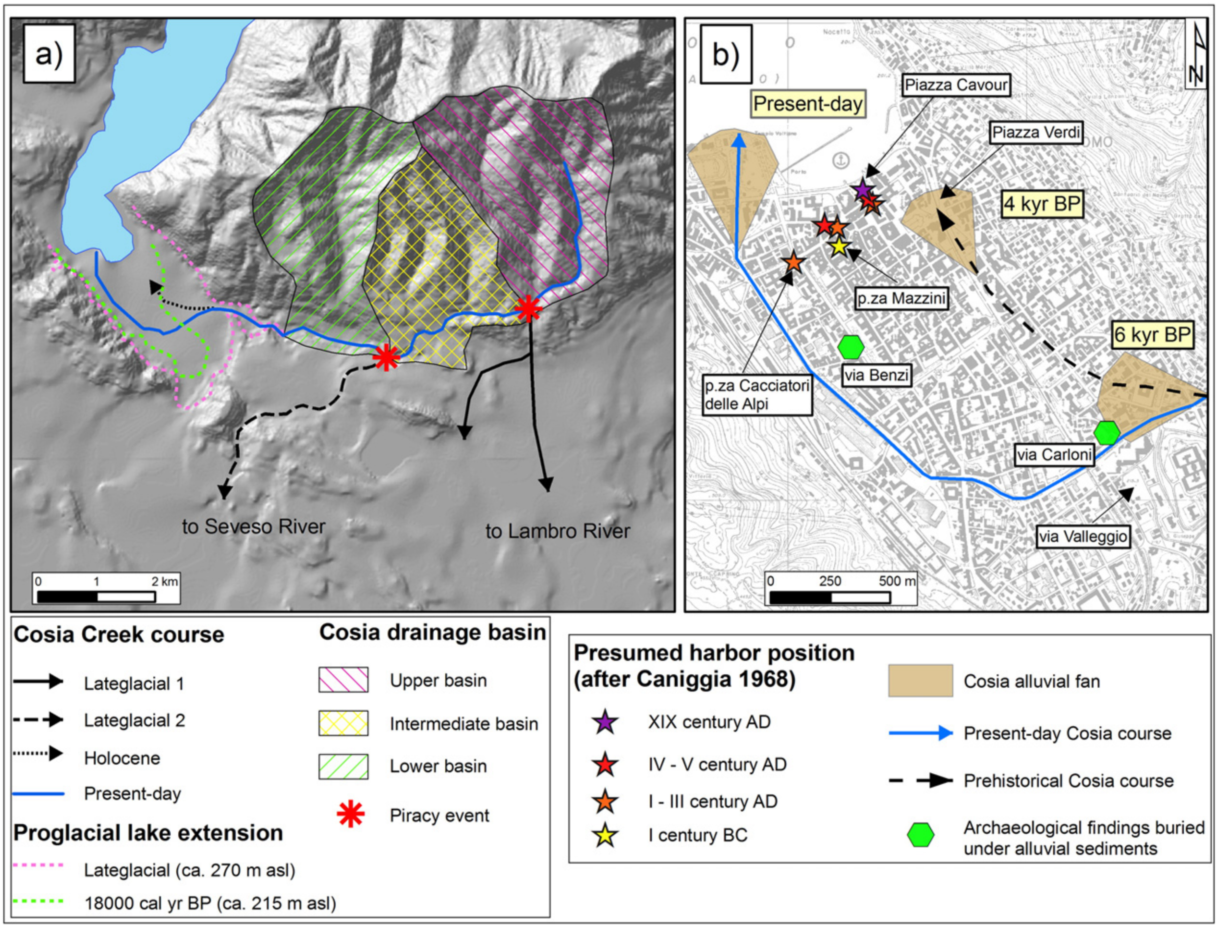

Fig. 11. a) Cosia Creek probable courses during Early Holocene and their drainage basin, which has been subdivided into upper, intermediate and lower basins; b) Stratigraphic and archeological findings that helped to identify the Holocene position of the Cosia alluvial fan and the evolution in the position of the town harbor.

of the basin. The Cosia Creek drainage basin was limited to its lower part: the upper and intermediate basins were tributaries of the Lambro and Seveso River basins (Fig. 11a), probably due to glacial deposits damming the paleo-Cosia course. With the erosion of these deposits, the drainage basin of Cosia Creek extended to the east through at least two piracy events, reaching its present-day configuration (Ascheri, 1972; Orombelli, 1976). The last piracy event probably occurred just before 6 cal kyr BP, when the drainage basin expanded from 7 km^2 to approximately 20 km^2. This expansion occurred in an area rich in glacial deposits, which were rapidly eroded and transported into the lake.

Stratigraphic logs and ^{14}C dates (see Table 1) helped in identifying the position and the adjustments of the local drainage courses. The Cosia alluvial fan reached the areas of *via Valleggio* (ca. 5.8 kyr BP) and *Piazza Verdi* (ca. 4.5 cal kyr BP), which points to a fast progradation of the Cosia Creek delta over the palustrine basin (Fig. 11b). This was promoted both by natural and anthropogenic components and resulted in the deposition of 10 to 25 m of gravels and sands. A strong increase in

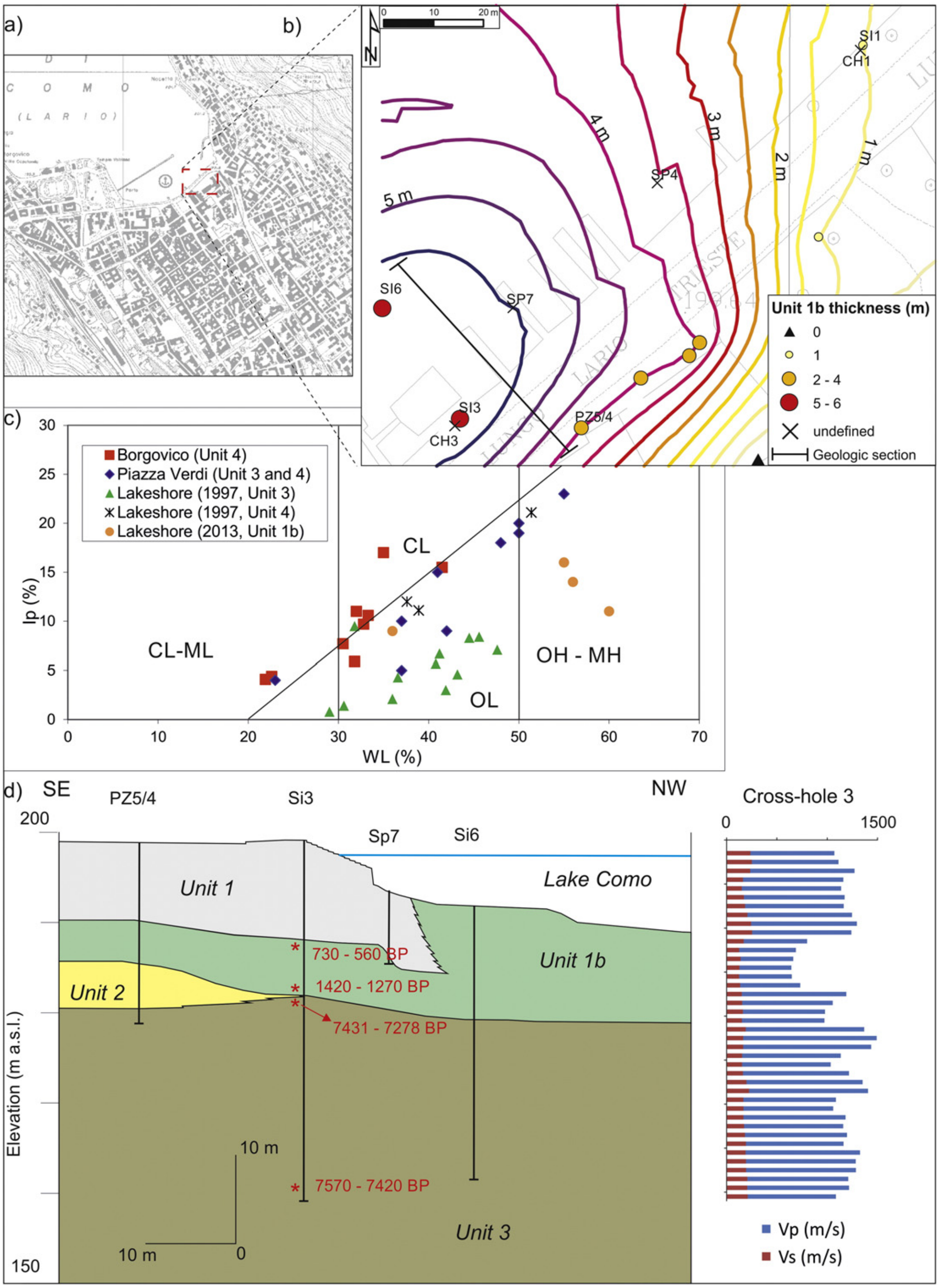

Fig. 12. a) Location of the supplementary coring campaign performed in 2013; b) Isopach map of Unit 1b including location of the geological section shown in d); c) Casagrande plasticity chart for samples of Units 1b, 3 and 4; d) SE–NW oriented geologic section, ^{14}C dating and results of the cross-hole test CH3.

Table 2
Physical and mechanical parameters of the stratigraphic units. Data derives from the integration of new drillings performed on the lake-shore with *Piazza Verdi* and other available probes.

	Units 1–2	Unit 1b	Units 3–4	Unit 5
N-value (SPT)	5–30; > 100 (coarse sediments)			40–50
Tip resistance (pocket penetrometer) (kPa)		25–50	40–150	
Cone resistance Qc (MPa)	1–10	0.2–0.5	1.6–2.4	
Unit weight (kN/m^3)	19.0	13.5–14.4	18.0	20.0
Permeability coefficient k (m/s)	10^{-5}–10^{-6} (Unit 1) 10^{-2}–10^{-8} (Unit 2)	10^{-6}–10^{-8}	10^{-6}–10^{-8}	
Friction angle (°)	34	21	24	32
Cohesion c′ (kPa)	0	0	0	0
Undrained cohesion Cu (kPa)	0	10	50	0
Young modulus E (MPa; from CPTU tests)	12–15			
Confined modulus Mo (MPa; from CPTUs and oedometric tests)		0.6–1.3	1.6–2.6 (depth 15–40 m) 3.7–4.0 (40–55 m)	

microscopic charcoal influx occurred about 5.6 cal kyr BP (Martinelli, 2014) and reflects human influence, in particular the use of fire in deforestation. The fast progradation of the Cosia Creek delta abruptly ceased ca. 4 cal kyr BP; in this case, natural (e.g., lack of source material, lake-level oscillations) or human factors (e.g., better human control of the territory) may have contributed.

The lake-shore position was stable up to ca. 2 cal kyr BP, when Roman colonization occurred. The settlement of the town involved surface-water control and diversion of Cosia and Valduce Creeks. The subsequent historical evolution deals with several expansions and the migration of the harbor towards the North (Fig. 11b). Locally, archeological evidence is buried below alluvial deposits, pointing to Cosia Creek floods (e.g., *via Carloni* and *via Benzi* sites; Uboldi, 1993). Our research substantially confirms the model based on the archeological studies (Caniggia, 1968; Jorio, 2004; see Section 3.2). Over the last three centuries ca. 200 m of lake margin progradation has occurred, due to land reclamation and anthropic fill in lake-shore areas.

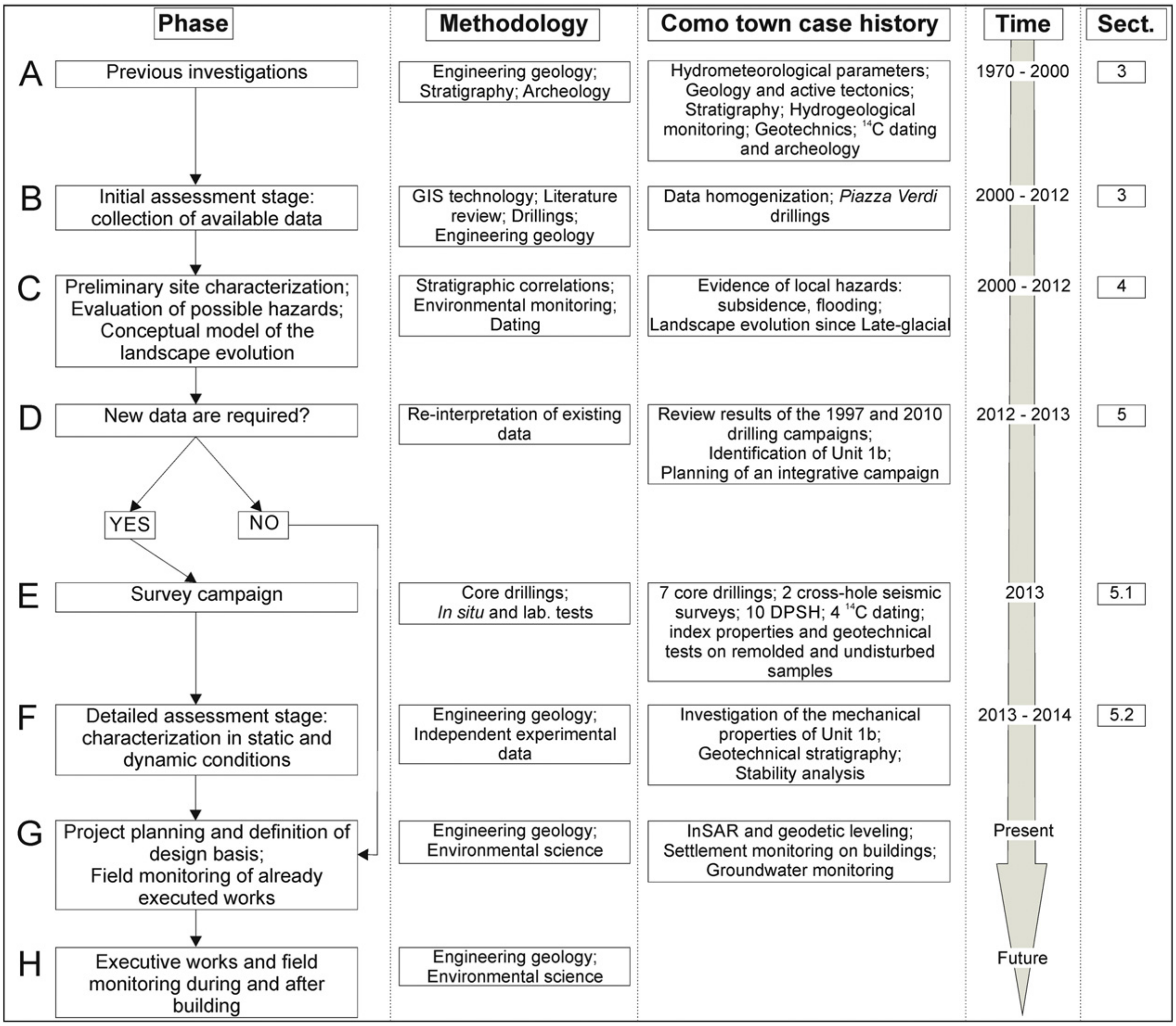

Fig. 13. Conceptual flow of the research; we apply this model to the town of Como during the planning for a project for protecting the town from the flood hazard. The column Sect. refers to the section in the present paper in which every phase is discussed.

5. Applying the model: lake-shore area

In order to avoid, or at least minimize, economic loss due to lake-shore flooding, a new integrated defense system against floods is under construction on the Como lake-shore. It consists of rows of mobile gates intended to protect the town during events causing very high lake levels. This facility is critical for urban management in the next decades. During a revision of the project for this facility in 2012–2013, we had an opportunity to apply our model to characterize the interactions between the facility, the physical environment and the local urban setting. We anticipated that the most critical location for engineering works would have been in the eastern part of the lake-shore, where thicker sediments with very poor mechanical properties (Unit 1b) were expected. Our model suggested that Unit 1b settled after the course of Cosia Creek was altered by the Romans, so we presumed a very young (approximately < 2 kyr) age for these deposits. Even if only a few meters thick, Unit 1b was the most critical unit but its role in engineering and environmental characterization had never been highlighted. Therefore, we planned and carried out a new drilling campaign in order to (i) characterize in detail subsoil properties, both in static and dynamic terms, as prescribed by current national laws and (ii) identify possible submerged structures, that could influence project design, choice of operative techniques and related economic costs.

5.1. In situ and laboratory tests

The supplementary investigations were conducted in 2013: two continuous core drillings 40-m deep (SI1 and SI3) were made, and three cores (SI6, SP4, SP7), 10- to 30-m deep were extracted on the promenade and on the lake bottom, respectively. Two other cores (CH1, CH3) were drilled adjacent to SI1 and SI3 for cross-hole surveys, without recovering the sediments (Fig. 12b).

For the first time, deposits of Unit 1b were fully investigated. The unit consists of organic silts, very rich in archeological remains and brick fragments, and is up to 6 m thick. ^{14}C dates yielded an age of a few centuries AD (upper to lower Middle Ages; Table 1). AGIS-based model allowed us to estimate isopachs of the unit (Ferrario et al., 2013; Fig. 12b).

Drillings and SPT allowed us to identify an anthropic fill placed to protect lake-shore infrastructure. Using DPSH (Dynamic Probing Super Heavy) penetration tests, the wedge shape of this fill, which is 3-m thick near the lake and becomes thinner to the north, was assessed. Cross-hole seismic tests allowed us to map the variation in P- and S-seismic wave velocities with depth, to define the seismic category of the sedimentary sequence and to evaluate its elastic parameters (Young's modulus, Poisson's coefficient) under dynamic conditions.

Laboratory tests were primarily focused on defining index properties of Unit 1b. Water content, plasticity, triaxial and oedometric tests were conducted. Fig. 12c shows the Casagrande plasticity chart, comparing previous data on Units 3 and 4 and the new results. Finally, a geologic section perpendicular to the lake-shore was drawn (Ferrario et al., 2015; Fig. 12d) and a stability analysis was conducted.

5.2. Geotechnical stratigraphy

The integration of stratigraphic data and geotechnical parameters enabled us to formulate a geotechnical stratigraphy. The main geotechnical parameters are listed in Table 2. Some units were combined, due to the similarity in their index properties; however, the facies distinction had a clear role for landscape reconstruction.

- *Unit 1: Recent anthropic fill (<200 years)*
  Anthropic fill, reworked materials and recent deposits; medium-coarse sands and fine gravels with silty matrix and sparse pebbles; bricks and vegetal remains are widespread. Locally, protective fill for coastal infrastructure and archeological materials (pottery, leather tiers) are present; in the *Piazza Cavour* area, thickness reaches 15 m. Low to medium permeability (10^{-5} to 10^{-6} m/s).
- *Unit 1b: Organic silts (Roman to Middle Ages)*
  Plastic silts very rich in organic matter and water; locally sand, clay and peat are present, vegetal remains are widespread. The unit reaches a maximum thickness of 6 m and settled in a low-energy depositional environment, presumably a sheltered harbor or a dock; sparse reworked brick fragments were found up to 14 m below ground surface and suggest a historical age for the deposits, as confirmed by ^{14}C dates. Low to very low permeability (10^{-6} to 10^{-8} m/s); water content = 60–90%, Liquid limit LL = 60%, plasticity chart group OH.
  Confined modulus derived from CPTUs and oedometric probes (e.g., Mitchell and Gardner, 1975) ranges between 0.6 and 1.3 MPa. Undrained cohesion from triaxial and compression tests ranges between 6 and 15 kPa.
- *Unit 2: Alluvial deposits (Holocene)*
  Coarse sands and fine gravels, sparse pebbles; locally finer horizons are present. This fluvial facies is related to the local drainage network and hosts groundwater circulation due to medium to high relative permeability (10^{-2} to 10^{-5} m/s). The thickness rapidly decreases from the south towards the lake. Geotechnical parameters are similar to those of Unit 1.
- *Unit 3: Organic silts (Late Pleistocene–Holocene)*
  Clayey silts (OL group in the plasticity chart), with coarser horizons and vivianite; on the western side of the lake-shore, sandy silts predominate (Unit 3a), while on the eastern side, the unit is richer in clay (Unit 3b). Decomposed vegetal fragments are dispersed or organized in aggregates or lenses. A laminated structure, with alternating thin organic and thicker inorganic strata is present; the laminations are generally sub-horizontal, but sometime inclinations of up to 40° or flame-structures are recorded, the latter interpreted as gas-emission features. The unit represents a lacustrine–palustrine depositional environment and has low permeability (10^{-6} to 10^{-8} m/s). Grain-size analysis of 18 samples taken in the lake-shore area gave a mean value of 6.9 ϕ, a sorting of 1.84 and a skewness of -0.23; sediments can thus be defined as poorly sorted, coarse-skewed fine silts. The unit thickens from E to W, ranging from ca. 15 m to more than 40 m in *Piazza Cavour*. Water content ranges between 40 and 70%, close to the liquid limit. The unit is widespread in the entire urban area and is largely responsible for the subsidence, due to its high compressibility.
- *Unit 4: Inorganic silts (Late Pleistocene)*
  Clayey silts (CL-ML group in plasticity chart), widespread in the whole urban area below ca. 40–60 m depth; locally a sandy facies has been recognized (Unit 4a), but the unit is typically composed of finer material (Unit 4b). Dropstones are widely distributed, suggesting a glaciolacustrine depositional environment; index parameters are similar to those of Unit 3.
- *Unit 5: Glaciolacustrine sands (Late Pleistocene)*
  Medium to coarse sands, locally silts or gravels are present. On the lake-shore, the boundary with the uppermost unit generally lies at a depth of ca. 50–60 m, but on the eastern side it reaches a depth of 30 m. The unit is at least 50 m thick and hosts the deep aquifer; the few tests carried out at *Piazza Verdi* suggest a high shear resistance and low compressibility.

5.3. Model reliability and insights on the historical evolution of the town

The results from our investigations broadly confirmed our hypothesis and thus the reliability of the model itself. Indeed, in the eastern part of the lake-shore, we found both recent organic silts (Unit 1b) and submerged anthropic structures. These finds enable us to follow different phases of the historical evolution of the area: during the Roman age, it was a shallow-waterlake-margin environment, where fine sediment very rich in organic matter, wood and archeological remains settled. Then, the evolution of the city was a general expansion towards the north, obtained through several phases of land reclamation, that caused lake-shore migration (see Fig. 2) and harbor relocation (see Fig. 11).

6. Conclusions

This study analyzes the Late Quaternary environmental evolution and ongoing hazard challenges to the town of Como, addressing the interaction between engineering construction and the geoenvironment. The conceptual flow leading to the applied approach (Fig. 13) is derived mainly from the one developed for siting nuclear power plants and codified in a series of Safety Guides (e.g., IAEA, 2011). Safety requirements for nuclear installations are very strict, but the method is valid for planning every kind of infrastructure or industrial plant; therefore, we adapted those criteria for the Como case study.

As a summary of our study, we provide a general workflow (Fig. 13) in which the importance of a robust organization and control over construction works is highlighted, as well as a proper communication to people. The workflow is intended to be used not only by geologist or engineers, but also by people without technical expertise, such as politicians, decision makers, architects, planners and the general public.

The environmental framework and the historical evolution of the area have been investigated since 1970 (Phase A). The initial assessment stage of our study was based on a thorough revision of available data, systematic monitoring and new data acquisition, including the drilling of two scientific boreholes in *Piazza Verdi* (Phase B). The collection of ca. 250 core logs and geotechnical data allowed us to define the stratigraphic architecture and mechanical properties of the sedimentary basin beneath the town. The hydrogeological setting was defined by means of long-term groundwater monitoring. The recent evolution of the town was reconstructed by integration of geomorphology, archeological finds and historical documents. We analyzed lake flood records and estimate long-term subsidence rates (2–4 mm/yr since Late-glacial) and human-induced ones (ca. 2 cm/yr during 1950–1975).

The reconstruction of a history of landscape evolution allowed us to identify local geological hazards that threaten Como town, mainly lake flooding and subsidence (Phase C). In 2012, we revised the engineering planning of a strategic facility for the mitigation of the flood hazard, using our model to evaluate possible interactions between the facility and the local urban environment. Reinterpretation of existing data indicated the existence of a sedimentary package (Unit 1b) with very poor mechanical properties that had previously not been investigated (Phase D). In our opinion, existing data were not sufficient for a complete site characterization, therefore we planned several new studies. Investigations in 2013 include drill of seven cores and the execution of several geological and geotechnical probes (Phase E). These further investigations allowed us to make a detailed assessment of the site, defining the index properties suitable for engineering planning in both static and dynamic conditions (Phase F).

Our results are at present being used as input data for revising the project and choosing better operative techniques. The possible modifications induced by the facility or by the related engineering works are currently being evaluated through integrated monitoring, including remote sensing and geodetic leveling, clinometric measuring on buildings and hydrogeological monitoring (Phase G). New executive phases will start in the near future for the facility completion; measurements will continue, both during and after completion of the proposed works (Phase H). The facility is planned for protecting the town against floods with a recurrence frequency of 50 years, so an appropriate survey of the local setting has to continue at least for several decades.

This paper presents a case history that had immediate consequences for territorial management; however, we believe that the same approach has wide applications and can be used well beyond this single case. The methodological framework summarized in Fig. 13 highlights the primary role that multidisciplinary environmental research should play in understanding natural hazards and their relations with human infrastructure, especially in densely inhabited regions.

The adopted techniques are easy to access and generally of low-cost and they can significantly improve the quality and reliability of engineering projects. Case histories of failures of geotechnical engineered systems clearly demonstrate that a proper understanding of the geological setting is not always achieved.

Our work highlights that data obtained by different methods complement and reinforce each other because various spatial and temporal scales are investigated. The integration of the archeological record helps in filling the gap between geological and historical studies in cases where written records are missing or incomplete. This kind of research necessarily requires cooperation among different specialists in earth science. Our work can also unfold new perspectives at the local scale, for instance for archeological studies aimed at revealing the migration of the harbor position since Roman times.

Urban planning and heritage management are both themes of worldwide relevance, in which a proper geological and engineering practice has a clear role. This is particularly true in urban environments, where poor or unknown ground conditions and vulnerable existing urban fabric are challenging tasks that have to be addressed during design and construction works. Thus, the ability to distinguish between natural and human-driven components of the local landscape is of crucial importance.

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