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Urban Water Management in Milan Metropolitan Area, a review

Gestione delle acque in ambito urbano nell'area metropolitana di Milano, una review

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Riassunto

Il crescente tasso di urbanizzazione e l'estremizzazione dei fenomeni climatici rappresentano una costante minaccia per la gestione della risorsa idrica in ambito urbano. L'area metropolitana di Milano (Regione Lombardia, Nord Italia) negli ultimi decenni è stata interessata da a) frequenti eventi piovosi estremi, responsabili dell'esondazione dei principali corsi idrici superficiali, e b) da problematiche di gestione della risorsa idrica sotterranea, sia dal punto di vista quantitativo (es. interazione con le infrastrutture sotterranee) che qualitativo. Inoltre, il crescente utilizzo di sistemi geotermici alimentati ad acqua di falda impone ulteriori considerazioni. Questo lavoro analizza la letteratura disponibile nell'area relativamente alle esondazioni superficiali, quantità, qualità e temperatura delle acque di falda. Infine, viene proposta una discussione per comprendere a) quali approcci possano favorire una gestione efficace della risorsa idrica sia superficiale che sotterranea, b) quali punti di contatto emergano tra questi due aspetti del ciclo idrico urbano, e c) quali possibili interventi urbanistici possano contribuire ad una gestione integrata e funzionale della risorsa idrica, riducendo anche alcune problematiche attuali.

Abstract

The increasing rate of urbanisation and extreme climatic events represent a constant threat for urban water resources management. In recent decades, Milan Metropolitan Area (Lombardy Region, Northern Italy) has been affected by a) frequent extreme rainfall events, responsible for the flooding of major surface water courses, and b) groundwater management problems, both from a quantitative (i.e. interaction with underground infrastructures) and qualitative point of view. Moreover, the increasing use of groundwater geothermal systems also requires further considerations. This work analyses the literature available in the area regarding surface floods, groundwater quantity, quality, and temperature. Finally, a discussion is provided to understand a) which approaches could promote an effective management of both surface water and groundwater resources b) which points of contact emerge between these two aspects of the urban water cycle, and c) which possible urban interventions could contribute to an integrated and functional management of water resources, also reducing some current issues.

Introduction

Urban areas are complex environments, where human interests strongly interfere with natural processes (Niemczynowicz, 1999). As the urban population is expected to grow in the next decades, reaching 70% of the world population by 2050 (Un-Habitat, 2012), managing the impact on natural environments becomes essential (Mitchell, 2006). This rapid urbanisation rate, together with climate change effects and inappropriate urban planning policies have resulted in water issues (Brown et al., 2009; Butler et al., 2014). According to Oral et al. 2020, "urban water refers to all water that is present in urban environments, including natural surface water, groundwater, drinking water, sewage, stormwater, flood overflow water and recycled water". Among these, stormwater and groundwater management are widely debated topics (Foster et al., 2013).

Stormwater is the main driver of surface floods (O'Donnell and Thorne, 2020). These can lead to physical disturbances, determining negative economic, social, and infrastructural impacts (Li et al., 2020). Removing runoff from urban areas through urban drainage systems is necessary to prevent flooding episodes (Yazdanfar and Sharma, 2015), also addressing the concept of the hydraulic invariance. This principle requires that the runoff from the outlet of a transformed area is maintained intact or below a threshold limit (Botticelli et al., 2018; Masseroni et al., 2019). Traditionally, human-engineered grey infrastructures were adopted (Li et al., 2020), including pipes, pumps, or detention ponds (Viavattene and Ellis, 2013). However, urbanisation and more frequent, extreme, and intense stormwaters could overwhelm the drainage capacity of these traditional systems (Pahl-Wostl, 2007; Brown et al., 2009; Nguyen et al., 2019). Moreover, the ageing of these structures constitutes another issue (Green et al., 2021); hence, evolving towards sustainable drainage approaches, to support traditional systems, is required (Li et al., 2020). These systems, including best management practices, low impact development, water sensitive urban design and sustainable urban drainage systems (SUDS) (Nguyen et al., 2019) are more adaptive and resilient to climate change, also enhancing the natural environments of urban areas (Tzoulas et al., 2007). Their adoption must be site-specific, selecting the most suitable infrastructures through strategic planning (Li et al. 2020), as sometimes dense urban environments limit the implementation of some SUDS (Viavattene and Ellis, 2013).

Within an integrated urban water management, SUDS to control stormwater must be interconnected with groundwater (Schirmer et al., 2013). Groundwater management sometimes becomes difficult as groundwater is considered a hidden resource (La Vigna, 2022), being "out of sight and out of mind" (Shanahan, 2009). The vertical development of urban areas has increased the subsurface importance (Bobylev, 2016): this requires an integrated management of groundwater with other underground resources, including space, materials, and heat (Li et al., 2013). A strong relationship between groundwater and underground infrastructures (i.e. basements, car parks, subway lines) has been detected in many cities worldwide (Wilkinson, 1985; Hayashi et al., 2009; Lamé, 2013; Allocca et al., 2021), caused by deindustrialization processes that triggered rising water table levels after intense drawdown periods. Industrial activities and unregulated waste management practices also affected groundwater quality, further deteriorating the resource (Wakida and Lerner, 2005; Burri et al., 2019). Hence, groundwater quantity and quality have been major concerns of urban groundwater management; recently, the attention moved also to groundwater temperature (Bayer et al., 2019). Groundwater represents a valuable energy reservoir (Schirmer et al., 2013), favouring the adoption of shallow heating and cooling systems for buildings, thus saving fossil fuels and containing greenhouse gases emissions (Lo Russo et al., 2012). However, anthropogenic activities directly influence the subsurface temperature, yielding local subsurface heating (Noethen et al., 2022): hence, a proper management is necessary to avoid thermal interference, water quality degradation, and alteration of the microbial community (Griebler et al., 2016; Riedel, 2019).

All these considerations imply a strict cross-sectional collaboration between engineers, city planners and public stakeholders to overcome unfamiliarity with other management domains, the applied and available technologies (Niemczynowicz, 1999; Viavattene and Ellis, 2013), thus supporting decision-making processes.

This work investigates surface flood risk and groundwater management (quantity, quality and temperature aspects) for Milan Metropolitan Area (Lombardy Region, Northern Italy), through a state of the art analysis on the available literature. This area has been selected for this study due to its dynamic behaviour, as it is currently undergoing an urban transformation involving both surface and subsurface compartments. Frequent stormwater events have occurred in the last years, severely impacting the domain: hence, considering the most suitable strategies to provide a sustainable transformation in response to climate change effects is needed. Finally, some future perspectives concerning this urban transformation will be discussed. All these aspects, analysed simultaneously, could be useful to support the stakeholders in urban water management.

Study Area

Milan is a strategic and economically important urban centre for Northern Italy, located in the middle of Po Plain (Fig. 1a). It is highly populated and urbanised, hosting 1.4 million people (Istat, 2011). The climate is humid subtropical, with cold winters and hot summers characterised by thunderstorm events (Mariani et al., 2016). Historically, intense industrial and agricultural activities (Bonomi et al., 2009; Pulighe and Lupia, 2019) characterised the area. The former were mostly conducted in the northern sector, largely urbanised as the downtown, while agricultural activities still take place in the West and South (Fig. 1).

Due to a vast surface water network, Milan is considered a "City of Water". Since the 12th century the Navigli canals (Naviglio Grande, Naviglio Pavese, and Naviglio Martesana)

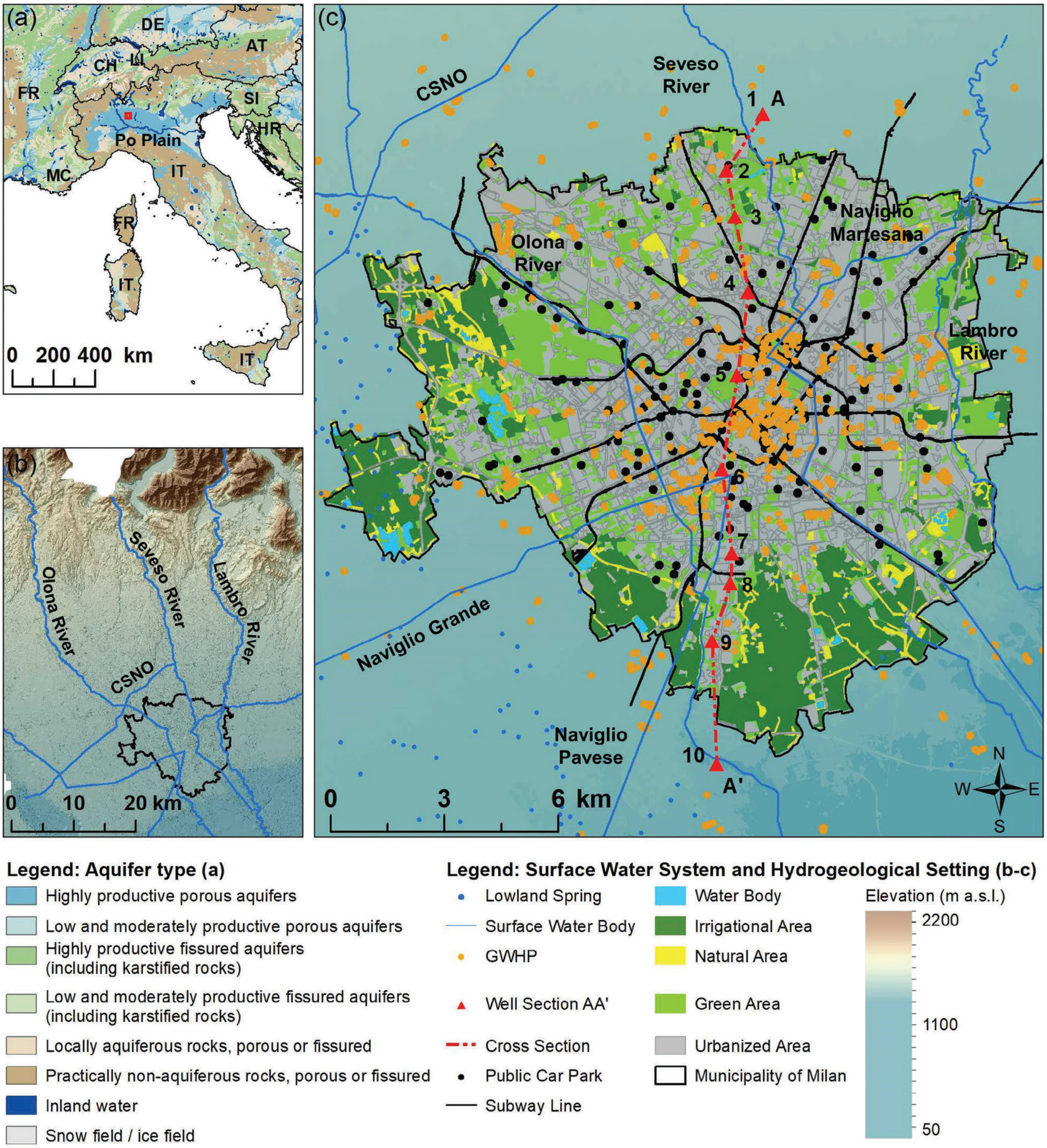


Fig. 1 - a) Geographical setting of the study area, showing the International Hydrogeological Map of Europe (Duscher et al., 2015); b) Surface water network of the study area, including main rivers; c) Main hydrographic (lowland springs and surface water network), anthropic elements (subway tunnels, underground car parks and groundwater heat pumps - GWHPs) and land use classes from Dusaf 6.0 (Regione Lombardia, 2021). Information regarding GWHPs, obtained from Regione Lombardia 2021, is updated at July 2021. Line AA' points to the cross section location that is visible in Figure 2.

Fig. 1 - a) Inquadramento geografico dell'area di studio, che mostra la Mappa Idrogeologica Internazionale d'Europa (Duscher et al., 2015); b) Reticolo idrico superficiale dell'area di studio, che include i fiumi principali; c) Elementi idrografici principali (fontanili e reticolo idrico superficiale), antropici (linee metropolitane, parcheggi sotterranei e pompe di calore a circuito aperto) e classi di uso del suolo provenienti dal Dusaf 6.0 (Regione Lombardia, 2021). L'informazione relativa alle pompe di calore a circuito aperto, ottenuta da Regione Lombardia 2021, è aggiornata al mese di Luglio 2021. La linea AA' indica la posizione della sezione visibile in Figure 2.

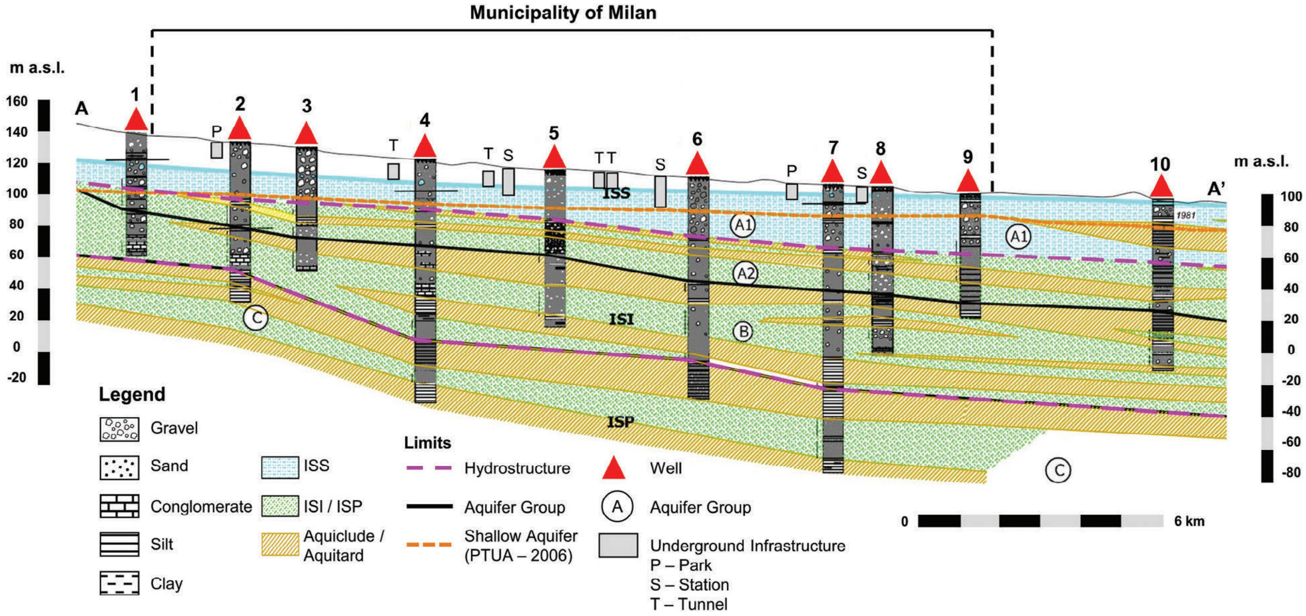


Fig. 2 - Geological profile of N-S cross section AA' of the study area, readapted from Regione Lombardia (2016) and Sartirana et al. 2022a. The aquifer group classification from Regione Lombardia & ENI (2002) is also provided.

Fig. 2 - Profilo geologico della sezione N-S AA' dell'area di studio, riadattato da Regione Lombardia (2016) e Sartirana et al. 2022a. Viene anche fornita la classificazione degli acquiferi di Regione Lombardia & ENI (2002).

were used to deliver food and construction materials to the city, also providing water for irrigation activities. These canals are part of a wide hydrographic network including also Olona, Seveso and Lambro rivers, originating from the Northern foothills (Fig. 1b). These three rivers, with elongated and narrow basins, characterise the "Hydraulic node of Milan" (Gambini et al., 2024). Olona and Seveso rivers are partly culverted within the city. Intense urbanisation has increased the effect of stormwaters, triggering different flood events in the last decades. Hence, a series of hydraulic works were realised in the northern parts of these basins to reduce the discharge flowing to Milan. The main intervention along the Seveso River was the Canale Scolmatore di Nord Ovest (CSNO) to divert excess water at the municipality of Paderno Dugnano.

Lately, Milan has been classified as an alluvial groundwater city, lying in an alluvial depositional basin (La Vigna, 2022), hosting highly productive porous aquifers (Duscher et al., 2015) (Fig. 1a). The geological and hydrogeologic setting was deeply investigated in the past (Regione Lombardia and ENI Divisione AGIP, 2002). A recent characterization identified three main hydrostructures: a shallow hydrostructure (ISS), an intermediate hydrostructure (ISI) and a deep hydrostructure (ISP) (Fig. 2) (Regione Lombardia, 2016). ISS is mainly composed of sand and gravel, and has an average thickness of 50 meters. ISI is mostly characterized by the same lithologies, with an increased presence of silty layers. ISP lithological composition is more uncertain due to lacking geological information.

Changes in ground slope and sediment permeability from coarse (i.e. gravel and sand) to fine (i.e. silt and clay) materials from North to South favour the formation of lowland springs in the western and south-western portions of the domain (Fig. 1c), inducing groundwater to outflow (De Luca et al., 2014) and favouring its use for irrigation.

Water table levels significantly varied over time. Groundwater was extensively exploited since the early 1960s for industrial needs, determining a groundwater minimum around 1975. The water table depth was around 30 metres from the ground in the northern sector. Intense precipitations, an economic crisis, and the development of new industrial technologies (Bonomi, 1999) triggered a gradual recovery of groundwater levels at the end of the '70s. Since the beginning of the '90s, water table levels rose again due to industrial decommissioning (i.e. maximum rise of about 10–15 metres at North). Consequently, some underground infrastructures including subway tunnels and car parks have been flooded (Cavallin and Bonomi, 1997; Gattinoni and Scesi, 2017; Colombo et al., 2018). Human activities significantly affected also groundwater quality of the shallow aquifer (Azzellino et al., 2019).

Recently, low-enthalpy geothermal systems have been installed for heating and cooling of buildings (Gizzi et al., 2023), especially in the downtown sector (Fig. 1c). Groundwater reinjection is allowed only in the shallow geological unit. For specific situations, groundwater is discharged in surface water canals to control the water table rising.

In 2019, the Plan of Government of the Territory (PGT) already outlined a further subsurface development, including new underground infrastructures. Hence, an urban underground management plan is required to handle all the subsurface resources, considering also groundwater/underground infrastructures interactions.

Review Structure

Surface flood risk and groundwater management have been analysed globally but also at city scale (Mudd et al., 2004; Vázquez-Suñé et al., 2005; Schirmer et al., 2013; Nkwunonwo et al., 2020; Guo et al., 2021; Cea and Costabile, 2022; La Vigna, 2022). Examining these water sectors together could help identify their interactions. Firstly, surface flood risk is examined, not strictly for Milan municipality, as a catchment-based perspective is needed (Seher and Löschner, 2018). Subsequently, groundwater quantity, quality and temperature themes are analysed. Finally, some considerations regarding urban water management perspectives have been discussed.

Surface Flood Risk

Since 1976 an average of 2.5 stormwater events per year occurred (Masseroni et al., 2017) along the Seveso River, triggering flooding events. The events of 18 September 2010 and 8 July 2014 are among the most intense, provoking damages for more than 20 million Euros. Recently, on 31 October 2023 water flowed out of manholes, generating fountains (Taramelli et al., 2022) and damaging both surface and subsurface infrastructures (i.e. basements, subway stations), causing street closures and interruption of public services.

Flood risk was investigated under different perspectives: institutional; non-structural tools (including rainfall-runoff modelling to support early-warning systems and sustainable measures to mitigate flood risk); buildings vulnerability; psychological.

Lambro and Seveso River basins were analysed (Vitale et al., 2020; Vitale and Meijerink, 2021) for the legislative framework to understand how resilience has been institutionalised by local authorities to mitigate flood risk. Three types of resilience can be distinguished: engineering, ecological and socio-ecological (Vitale and Meijerink, 2023). Engineering resilience is based on hard control infrastructures (i.e. dams, dykes) to reduce flood probability; ecological resilience is referred to an adaptive capacity to reach a new system equilibrium. Finally, socio-ecological resilience describes how a community can cope with social and environmental changes. For both rivers, engineering resilience was the dominant approach, as historically occurred also at national level (Vitale and Meijerink, 2023). Continuous threats affecting Seveso River facilitated the adoption of an emergency approach, favouring a securitization process (Vitale and Meijerink, 2021). A few institutional actors (Lombardy Region and Municipality of Milan) adopted a top-down approach, excluding other local authorities (i.e. upstream municipalities) from the decisional process. Financial resources were allocated mostly for hard engineering infrastructures, without addressing issues as poor water quality and ecological restoration. As for Lambro River, engineering resilience prevailed, fostering also the socio-ecological approach (Vitale et al., 2020). River ecological restoration, water quality improvement and biodiversity protection were further goals considered.

Early warning procedures are needed to support civil protection authorities, mitigate flood risk, and prevent damages to people and properties. An ensemble forecasting strategy (Ravazzani et al., 2016) integrated a meteorological model initialising FEST-WB hydrological model to simulate rainfall-runoff transformations. Short-range flood forecasting (i.e. one day in advance before the main peak flood) reproduced peak discharges of September 2010 and July 2014 stormwater events. However, at a small basin scale, local topographic conditions and fast-evolving events introduce modelling uncertainties, negatively influencing the early warning mechanisms. Moreover, as these basins have a response time of a few hours, flood predictions must be provided rapidly. Hence, different strategies were applied to evaluate less conventional meteorological tools to manage prediction uncertainty. A rainfall-runoff model named "Modello Idrologico Semi-Distribuito in continuo" (Brocca et al., 2013) was applied to the Seveso River basin (Masseroni et al., 2017); its easy applicability and low computational effort made it suitable to support decision-makers in flood risk management. Lombardi et al. 2018 adopted the "Shift-Target" approach along Seveso, Olona and Lambro basins; a single deterministic precipitation forecast was generated and spatially shifted along the domain to obtain different forecasts. Flood scenarios were reliable and obtained through a less computational demanding approach than probabilistic forecasts. Commercial microwave links were also considered in hydrological modelling, integrating rain gauges information in the Lambro catchment (Cazzaniga et al., 2022). The reliability of commercial microwave links in estimating rainfall fosters their adoption in early warning systems both in areas lacking traditional information or combined with the already existing monitoring network. Finally, Gambini et al. (2024) proposed a flood warning system based on catchment-specific rainfall thresholds, derived through a data-driven approach. These simple tools could support the civil protection warning system also without running a rainfall-runoff model, overcoming the uncertainty affecting small catchment forecasts.

As excessive urbanisation limits the adoption of structural measures, SUDS could be considered. Green roofs represent a possibility, reducing stormwater without soil consumption. Three hypothetical roof greening scenarios (conversion of 5, 30 and 100% of impervious roofs to green ones) were simulated to reduce peak runoff rates for Seveso catchment (Masseroni and Cislaghi, 2016). An initial saturation limits peak reduction and volume retention. However, a complete conversion to green roofs could decrease peak flows of around 30%, reducing sewer systems drainage. Permeable pavements and river restoration techniques were evaluated for Seveso River at the border between Milano and Bresso municipalities (Raimondi et al., 2020, 2021) to reduce the flood extension for different return periods. Positive effects were mostly detected for events with return periods lower than 10 years. Green roofs to reduce peak flows for frequent storms of small magnitude and further SUDS (i.e. detention tanks, wetlands) supporting traditional grey infrastructures were evaluated also in the surrounding municipalities of Sedriano (Ercolani et al., 2018; Masseroni et al., 2018), located outside of the considered basins, and Sesto Ulteriano (D'Ambrosio et al., 2022; D'Ambrosio and Longobardi, 2023).

Buildings vulnerability was assessed in a flood prone area of the city (Taramelli et al., 2022). Flood depth values were calculated considering July 2014 stormwater event. Combining this information with buildings intrinsic information (i.e. building and material type, presence of basement, period of construction), also considering Open-Source datasets, depth-damage curves were calculated to define potential damage. A monetary exposure was estimated for each building for return periods of 10, 100 and 500 years. This could support policy makers in public budgeting to set management priorities during floods to reduce buildings vulnerability.

Finally, a survey was conducted both in flood-prone and safe areas to investigate people's risk perception in occurrence of a near-miss event of October-November 2018 for the Seveso River (Bogani et al., 2023). In that case, flooding did not occur largely by chance. Notwithstanding, also people living in flood-prone areas perceived a low level of risk despite past frequent experiences. This could reduce the adoption of protective measures, causing serious economic consequences in case of real flood events.

The references analysed are listed in Table 1.

Groundwater Management

Groundwater Quantity

Different studies characterised the main factors influencing groundwater, both in past decades (Airoldi and Casati, 1989; Avanzini et al., 1995), and recently (De Caro et al., 2020b). Human activities mostly governed mass balance variations, triggering the drawdown phase for industrial needs from the '60s and the subsequent groundwater recovery due to industrial dismantling at the beginning of the '90s (Bonomi et al., 1998; Beretta et al., 2004). Natural factors (i.e. precipitations) partially contributed to groundwater oscillations (Airoldi et al., 1997; Beretta and Avanzini, 1998;

Tab. 1 - Papers analysed and perspective adopted to investigate surface flood risk. An X is used to indicate the river catchment analysed in each study.

Tab. 1 - Riferimenti bibliografici analizzati e prospettive adottate per studiare il rischio di alluvione. Una X viene utilizzata per indicare il bacino analizzato in ciascuno studio.

Surface Flood Risk Perspective	Main Outcomes	River Catchment			Reference
		Lambro	Olona	Seveso	
Institutional	Top-down approaches favoured engineering resilience	X			Vitale et al., 2020
				X	Vitale and Meijerink, 2021
Rainfall-Runoff Modelling	Integration of meteorological and hydrological models for short-term forecasting	X		X	Ravazzani et al. 2016
	Rainfall-Runoff model suitability to support decision-makers in flood management			X	Ravazzani et al., 2016
	Shift-Target as a valuable deterministic technique to evaluate flood scenarios	X	X	X	Lombardi et al., 2018
	Commercial microwave links data generate reliable rainfall estimates	X			Cazzaniga et al., 2022
	Rainfall thresholds support early warning systems without running hydrological models	X	X	X	Gambini et al. 2024
SUDS	Green roofs could significantly reduce peak runoff rates			X	Masseroni and Cislaghi, 2016
	River restoration techniques and pavements permeabilization could reduce floodable areas in Parco Nord			X	Raimondi et al., 2020
				X	Raimondi et al., 2021
	Designed-based approaches should be preferred to potential-based solutions to improve SUDS efficiency	X			D'Ambrosio et al. 2022
	Integrating flood control areas and green infrastructures contribute to reduce hydraulic risk	X			D'Ambrosio and Longobardi, 2023
	Green roofs effectively reduce peak flows of small magnitude storms				Ercolani et al., 2018
	Integrating green, grey and blue infrastructures reduces peak flows and improves water quality of combined sewer overflows				Masseroni et al., 2018
Vulnerability	Buildings monetary exposure could support public budgeting during flood events			X	Taramelli et al., 2022
Psychological	Near-miss events reduce risk perception, thus determining severe economic damages in case of occurring floods			X	Bogani et al., 2023

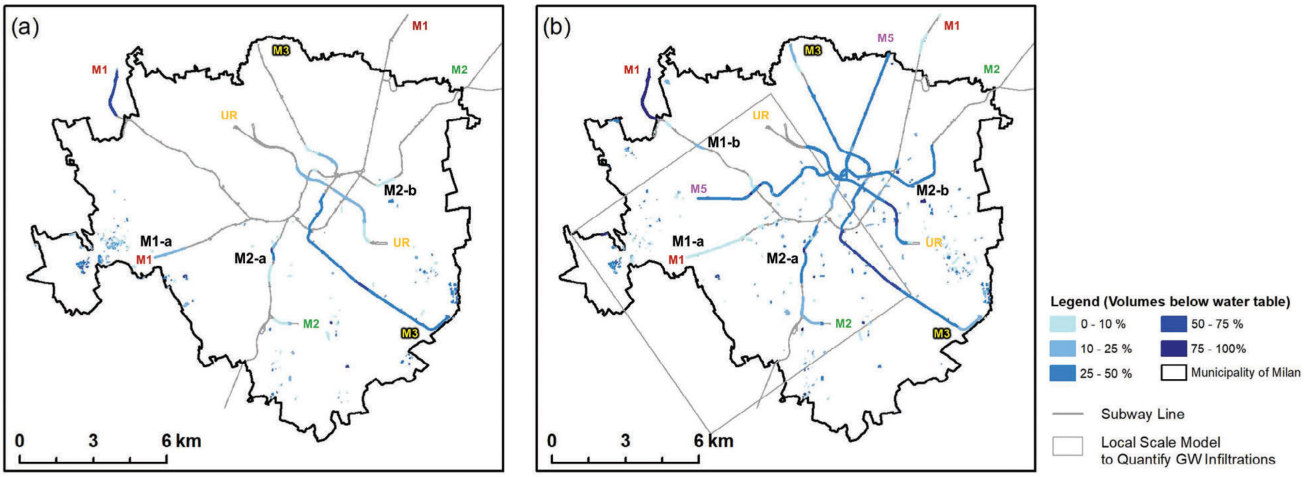
Bonomi, 1999). These latter were analysed through quasi-steady state models (Giudici et al., 2000, 2001), confirming that groundwater withdrawals largely control phreatic levels.

Groundwater oscillations reflect a variation in groundwater reservoirs over time. A quantitative evaluation was determined for the period 1979-2005 (Bonomi et al., 2010), providing valuable information to support water consumption management. A large amount of stratigraphic data, stored within Tangram database (Bonomi et al., 2014), allowed to parametrise the hydrogeological properties of the aquifers, as the effective porosity (Bonomi, 2009). Hence, both stored water and its mobile content were quantified. The former was around 33-34 billion cubic metres, while the latter ranged between 13-15 billion cubic metres. An increase of mobile water was calculated also for a limited portion of the subsurface (i.e. the area interested by groundwater oscillations between a groundwater minimum and maximum conditions), in the framework of evaluating groundwater/underground infrastructures interactions (Sartirana et al., 2022a).

This topic was significantly studied in recent years, as different portions of the subway network flooded (Colombo, 1999) due to water table rising. Mostly, groundwater flow numerical models were implemented, evaluating also the impact of underground infrastructures on groundwater flow. Groundwater/underground infrastructures interactions were evaluated both at limited portions of the domain (Colombo et al., 2017), or considering the entire municipality (Gattinoni and Scesi, 2017; De Caro et al., 2020a). At city scale, a stochastic approach was adopted (Colombo et al., 2018) to assess the hydrogeological hazard for subway lines in probabilistic terms. Locally, underground infrastructures act as barriers to groundwater flow, determining a water table rising upstream of the underground infrastructures and a decline downstream of up to ± 0.45 metres (De Caro et al., 2020a), also increasing the groundwater flow velocity below these man-made infrastructures (Colombo et al., 2017). Different groundwater scenarios were considered to discuss possible mitigation measures (i.e. blue-green infrastructures) to manage the potential risk associated with future water table rising. Recently, a local-scale numerical model was developed to analyse groundwater infiltrations into underground infrastructures, quantifying how submersion conditions could turn into real flooding episodes (Sartirana et al., 2022b). In this case, underground car parks were also considered. These underground infrastructures were identified in two previous studies. The former (Sartirana et al., 2020) discussed the construction of a 3D geodatabase to evaluate underground infrastructures volumes lying below the water table at different groundwater conditions. Three categories of underground infrastructures were considered: subway lines, underground car parks and private car parks lying below residential buildings. The latter (Sartirana et al., 2022a) dealt with a data-driven method that defined, through cluster analysis of groundwater levels time-series, four groundwater management areas where applying targeted strategies to cope with groundwater/underground infrastructures interactions. All these studies pointed out that the oldest subway lines, even if shallow, had a significant impact, as designed starting from the '60s without waterproofing techniques. The subway stations around Bisceglie (M1-a) and Bonola (M1-b) were frequently detected as critical for subway line M1, while Sant'Agostino (M2-a) and Piola-Lambrate (M2-b) were identified as severely impacted for line M2. The references analysed are summarized in Table 2, while the main underground infrastructures sections affected by groundwater flooding are visible in Figure 3.

Fig. 3 -Percentages of underground infrastructures volumes lying below the water table for a) the groundwater minimum condition of September 2007 and b) the groundwater maximum of March 2015. The image has been readapted from Sartirana et al., 2020. Coloured labels have been inserted at the initial and final stations for each subway line.

Fig. 3 - Percentuali dei volumi di infrastrutture sotterranee che si trovano al dì sotto della tavola d'acqua per a) la condizione di minimo idrogeologico di Settembre 2007 e b) la condizione di massimo idrogeologico di Marzo 2015. L'immagine è stata riadattata da Sartirana et al., 2020. Le etichette colorate sono state inserite in prossimità delle stazioni iniziali e finali di ciascuna linea metropolitana.



Tab. 2 - Papers analysed and perspectives adopted to investigate groundwater quantity topics.

Tab. 2 - Riferimenti bibliografici analizzati e prospettive adottate per studiare le tematiche degli aspetti quantitativi della falda.

GW Quantity Topic	Methodology	Study Scale	Reference
Factors Influencing Groundwater	Groundwater Levels Analysis	Provincial	Avanzini et al. 1995
			Airoldi et al. 1997
		Urban	Airoldi and Casati 1989
			Beretta and Avanzini 1998
			Bonomi et al. 1998
			Bonomi 1999
	Numerical Modelling	Regional	De Caro et al. 2020b
		Urban	Giudici et al. 2000
			Giudici et al. 2001
	Pumping Activities and Numerical Modelling	Local	Beretta et al. 2004
Groundwater Reservoir Evaluation	Hydrogeological Databases (Effective Porosity)	Provincial	Bonomi et al. 2010
		Urban	Sartirana et al. 2022a
Groundwater/Underground Infrastructures Interaction	Literature Analysis	Urban	Colombo 1999
	Numerical Modelling	Local	Colombo et al. 2017
			Sartirana et al. 2022b
		Urban	Gattinoni and Scesi 2017
			Colombo et al. 2018
			De Caro et al. 2020a
	3D geodatabase	Urban	Sartirana et al. 2020
	Data-Driven Techniques	Urban	Sartirana et al. 2022a

Groundwater Quality

Groundwater in urban areas could be affected by different anthropogenic activities, classifiable as: Point Sources (PS), hotspots releasing high concentration plumes; Multiple Point Sources (MPS), clustered sources related to low contaminant concentrations; Non-Point Sources (NPS), referred to anthropogenic activities conducted on large scales (Alberti et al., 2018).

This complicates the evaluation of the baseline groundwater quality status, not affected by human impacts. However, this remains fundamental to support a sustainable groundwater management (Zanotti et al., 2022). In this sense, Natural Background Levels were calculated through an hydrogeochemical characterization of the Milan metropolitan area (De Caro et al., 2017). Iron, manganese and arsenic exceeded the environmental water quality standards in the anaerobic portions of the subsurface; sodium, chloride, sulphate, and zinc concentrations resulted below the standards. Generally, groundwater quality resulted more impacted in urban areas than agricultural ones.

Regarding chlorinated solvents, one of the main historical PS contamination from trichloroethylene (TCE), tetrachloroethane (TeCA) and tetrachloroethylene (PCE) came from the former "Bianchi" chemical facility, located in the city of Rho (North-West of Milan). A slurry cut-off wall was the only containment measure up to 2006, when a hydraulic barrier was drilled. Geo-electrical methods were applied to detect the contamination up to 25 metres deep (Cardarelli and Di Filippo, 2009). Subsequently, numerical and transport models were developed to refine the conceptual model and understand the main parameters governing the contamination diffusion. Small-scale geological heterogeneities generate local hydrodynamic conditions, favouring a gravity-driven migration of the contaminants towards the deeper aquifer units (Pedretti et al., 2013) (i.e. up to 45 metres deep) originating secondary sources of contamination, hence limiting the effectiveness of the containment measures (Pedretti et al., 2012). Bonomi et al. (2009) developed a further numerical and transport model to analyse the exposure of southern drinking wells to this contamination; again, local geological conditions influenced the contamination paths, determining different impacts at diverse pumping stations, located in the north-western sector of the city of Milan, at about a distance of 9 km from the source of contamination. Novara pumping station resulted more affected than the close pumping stations of Assiano (partially impacted) and Baggio (almost not impacted).

Furthermore, PCE contaminations were evaluated in the Functional Urban Area of Milan, including also the cities of Monza and Rho, located at North-East and North-West of Milan, to characterise PS and MPS. Cluster analysis (CA) was applied to identify clusters related to background values and those linked to PCE hotspots (Alberti et al., 2016; Colombo, 2017). These latter were considered as plume source points in numerical flow and transport models (Alberti et al., 2016; Colombo, 2017; Colombo et al., 2019) to understand the orientation and extension of PCE plumes. Forward particle tracking helped to identify possible receptors impacted by contamination (Colombo et al., 2021). As regards MPS, particle backtracking was used to identify the potential source zone and the contaminant path (Alberti et al., 2018). To this end, the stochastic Null-Space Monte Carlo (NSMC) method allowed to generate hundreds hydraulic conductivity realisations, to manage the parameter uncertainty, realising scenarios pinpointing the most probable areas hosting MPS (Alberti et al., 2018; Colombo et al., 2020b; Pollicino et al., 2021b). Advective particle back-tracking was also used to identify PS in combination with the Weights of Evidence (WofE) technique (Pollicino et al., 2021a). This latter considered hydrogeological parameters (i.e. groundwater velocity, groundwater depth and recharge) and land use variation, not considered by the NSMC, potentially influencing the contamination. WofE was also applied to identify PCE MPS (Pollicino et al., 2019), also considering TCE and chromium (Pollicino et al., 2021c), hence identifying areas that deserve a groundwater management prioritisation. Finally, a multivariate statistical approach (Azzellino et al. 2019), combining Principal Component (PCA), Factor (FA) and Cluster Analysis (CA), was integrated with numerical modelling and geostatistics (Colombo et al., 2020a) to define Diffuse Pollution Background Levels (DBPLs), not attributable to specific PS, for PCE, TCE, trichloromethane and chromium. Five main clusters having different temporal profiles and background concentration levels were detected, evidencing how groundwater bodies should not be managed homogeneously, but through site-specific actions.

Different statistical methods were applied to assess groundwater vulnerability to nitrate pollution. Analyses were carried out applying standard WofE (Masetti et al., 2005, 2007; Sorichetta et al., 2011; Stevenazzi et al., 2017), modified WofE (i.e. multivariate WofE with Logistic Regression methods) (Sorichetta et al., 2012, 2013) or threshold values (Masetti et al., 2009) to deal with natural and anthropogenic contributions to nitrate pollution. Factors considered were: population density, nitrogen fertiliser loading, soil protective capacity, groundwater depth, unsaturated hydraulic conductivity, groundwater velocity and effective infiltration. Time dimension was also considered analysing satellite data to understand how groundwater vulnerability to nitrates varies as urban development and population increase (Stevenazzi et al., 2015). The north-eastern sector of Milan resulted the most vulnerable to nitrates. Population density, and consequently sewer-system losses, resulted the main source of nitrate; also, the high permeability of the unsaturated zone and the significant water table depth directly influence high nitrate concentrations. On the contrary, agricultural activities resulted negligible sources, also because localized where a shallow water table favours denitrification (Sacchi et al., 2013; Sorichetta et al., 2013). Isotopic investigations conducted at regional scale to identify the main sources, sinks and sites of accumulation of nitrates within groundwater confirmed these results (Sacchi et al., 2013).

CAP Group, the local water supplier that manages the Integrated Water Service (Servizio Idrico Integrato) for Milan Metropolitan Area, except for the city of Milan, also conducted isotopic investigations for nitrates and sulphates at basin-scale to support the decision system for Milan and Monza provinces (Gorla et al., 2016). Results for nitrates confirmed the impact of urban activities, while sulphate concentrations resulted mostly governed by farming activities.

Finally, emerging contaminants were analysed both in surface waters (Castiglioni et al., 2015, 2018; Palmiotto et al., 2018) and in abstraction wells for drinking water (Castiglioni et al., 2015; Riva et al., 2018), to assess human risk assumption. Different emerging contaminants categories were analysed including, pharmaceuticals, illicit drugs, perfluorinated substances and personal care products. Their occurrence in groundwater could be due to effluents of wastewater treatment plants, sewage network losses or industrial and agricultural residuals. Emerging contaminants highest concentrations were detected in shallow groundwater close to the main rivers flowing through the city (i.e. Lambro, Olona and Seveso), highlighting a possible contribution of surface waters to contamination. Contaminant concentrations increased from North to South along the Lambro River (Castiglioni et al., 2015). In the North of Milan, concentrations in groundwater and drinking water resulted higher than in the municipal area and in the South. Notwithstanding, analyses conducted at 27 drinking wells after the treatment process evidenced how the cumulative risk assessment was negligible, indicating the efficiency of the treatment techniques (Riva et al., 2018). Recently, carbamazepine in groundwater were analysed, relating their concentrations to the population composition of sub-municipal areas (Ebrahimzadeh et al., 2021).

The kinds of pollution source investigated and the investigation techniques are described in Table 3.

Groundwater Temperature

The Lombardy Region progressively increased its commitment to sustainability, promoting the adoption of renewable sources to limit greenhouse gases emissions (Aste et al., 2016). To fulfil the goals set by the European Union, the exploitation of shallow geothermal energy has increased, favoured by the energy potential offered by urban aquifers, as occurred for other European countries (Somogyi et al., 2017). In this sense, ground-coupled heat pumps (GCHPs, closed loop) and GWHPs (open loop) represent a solution for heating and cooling of residential buildings (Gizzi et al., 2023). As regards Milan, the regional legislative framework has facilitated the diffusion of GWHPs with respect to other Italian contexts (Berta et al. 2024). Also, the number of geothermal wells installed and the amount of groundwater withdrawn for energy needs in Milan Metropolitan Area have continuously risen in the last fifteen years, resulting significantly higher than any other Province within the regional domain (Cassani and Canobio, 2024).

Initially, research was mainly oriented towards the application of GWHPs at small spatial scales, both for

Tab. 3 - List of the main contaminants analysed, the used analysis techniques adopted and their bibliographic references. PS, MPS, NPS, DPBLs respectively stand for Point Source, Multiple Point Sources, Non-Point Sources, Diffuse Pollution Background Levels.

Tab. 3 - Elenco dei principali contaminanti analizzati, delle tecniche di analisi adottate e relativi riferimenti bibliografici. PS, MPS, NPS e DPBLs significano rispettivamente sorgente puntiforme, sorgenti puntiformi multiple, sorgenti non puntiformi e valori di fondo di inquinamento diffuso.

Contaminant	Kind of pollution source	Investigation Technique	Reference
Chlorinated Solvents (TCE, TeCA and PCE)	PS	Geo-technical methods	Cardarelli and Di Filippo 2009
		Numerical Modelling (SEEP, MODFLOW, MODPATH and MT3DMS)	Pedretti et al. 2012
			Pedretti et al. 2013
			Bonomi et al. 2009
		Data-Driven Techniques (CA) and Numerical Modelling (MODFLOW, MODPATH and MT3DMS)	Alberti et al. 2016
			Colombo 2017
			Colombo et al. 2019
			Colombo et al. 2021
		Numerical Modelling (NSMC) and WoFE	Pollicino et al. 2021a
	MPS	Numerical Modelling (NSMC)	Alberti et al. 2018
			Colombo et al. 2020b
			Pollicino et al. 2021c
		WoFE	Pollicino et al. 2019c
			Pollicino et al. 2021b
	NPS	DPBLs assessment through Data-Driven Techniques (PCA, FA, CA)	Azzellino et al. 2019
			Colombo et al. 2020a
Nitrate	NPS	WoFE	Masetti et al. 2005
			Masetti et al. 2007
			Sorichetta et al. 2011
			Stevenazzi et al. 2017
		Multivariate WofE and Logistic Regression	Sorichetta et al. 2012
			Sorichetta et al. 2013
		WofE and Satellite Data	Stevenazzi et al. 2015
		Threshold values	Masetti et al. 2009
		Isotopic investigations	Sacchi et al. 2013
			Gorla et al. 2016
Sulphate	NPS	Isotopic investigations	Gorla et al. 2016
Emerging contaminants	NPS	Liquid chromatography tandem mass spectrometry	Castiglioni et al. 2015
			Castiglioni et al. 2018
			Palmiotto et al. 2018
			Riva et al. 2018
		Data-Driven Techniques (PCA, FA, CA)	Ebrahimzadeh et al. 2021

industrial and residential sectors. Beretta et al. 2014 developed a flow and heat numerical model to optimise the exploitation of geothermal resources for the A2A Calore&Servizi cogeneration power plant of Canavese. GWHPs support the district heating network of the plant (Sparacino et al., 2007). Results highlighted how discharging part of groundwater withdrawn into a canal that feeds Lambro River helps avoid the thermal interference between pumping and reinjection wells. Regarding the residential sector, GWHPs performance can result lower than expected during the design phase, as verified for a multifamily building located in Milan (Biglia et al., 2021). Hence, defining proper control strategies to improve the system efficiency is required.

Different studies investigated the relation of GWHPs and district heating within the city, comparing them as alternative decarbonization measures (Famiglietti et al. 2021; Pozzi et al., 2021) or integrating GWHPs within the district heating network (Aste et al., 2017, 2020). In this second case, the combination of non-weather dependant GWHPs with photovoltaic systems was evaluated to realise a nearly-zero energy district, proving their efficiency to feed the energy requests of a small-size and low-temperature district thermal plant powered by wood biomass. Recently, GWHPs were analysed both at district (Famiglietti et al., 2023) and urban (Famiglietti et al., 2022) level through the life cycle assessment method to calculate the environmental footprint of buildings and their contribution to greenhouse gases emission.

GWHPs efficiency as cost saving technologies for energy production was also demonstrated by Aste et al. 2013, showing their wide applicability with respect to air heat pumps in the presence of severe air temperatures during winter season. In this sense, GWHPs could dampen the intensity of the urban heat island, reducing the heat dissipated by air pumps during summer (Schibuola and Tambani, 2022).

Worldwide, anthropogenic activities determined the development of the subsurface urban heat island, affecting groundwater thermal regime. The main natural and anthropogenic factors controlling groundwater temperatures within Milan were analysed through data-driven methods (cross correlation and trend analysis) and groundwater temperature-depth profiles, revealing how unsaturated zone thickness and underground infrastructures density mostly affect groundwater temperatures, with differences of up to three degrees between the downtown and the surrounding areas (Previati and Crosta, 2021a). Also, a city-scale 3D flow and heat transport model identified the most relevant heat sources (i.e. building basements, surface asphalt structures and underground tunnels), quantifying the geothermal potential and the effects of climate change and urbanisation (Previati et al., 2022). An increase in thermal energy is expected, thus suggesting the installation of further geothermal systems. Low enthalpy geothermal potential was analysed also at regional scale. Firstly, the thermal potential of both GCHPs and GWHPs was estimated to outline the most valuable shallow geothermal configuration for Milan Metropolitan Area (Previati and Crosta, 2021b). The alluvial aquifer resulted suitable to host both geothermal solutions, showing that thermal, geological (i.e. aquifer transmissivity) and hydrogeological (i.e. water table depth and groundwater temperature) factors control the geothermal potential. Subsequently, a surrogate model was developed to further analyse ground source heat pumps (GSHPs), revealing how groundwater advection could increase their thermal exchange potential (Previati and Crosta, 2024).

The references analysed and the main topic discussed for each GHPs application are described in Table 4. To the best of the authors' knowledge, the possible effects of groundwater temperatures variations on groundwater chemical and microbiological composition have not still been investigated through any research paper within the domain.

Tab. 4 - List of studies focusing on geothermal aspects for the study area and main fields of applications of geothermal heat pumps (GHPs).
Tab. 4 - Elenco degli studi focalizzati sugli aspetti geotermici per l'area di studio e principali campi di applicazione delle pompe di calore geotermiche (GHPs).

GHPs Application	Geothermal Considerations	Study Scale	Reference
Industrial	Thermal interference avoided discharging groundwater into a superficial canal	Local	Beretta et al. 2014
	Relevance of GWHPs to support district heating at city scale	Urban	Sparacino et al. 2007
Residential	GWHPs efficiency usually is lower than expected; control strategies are needed to evaluate and correct the system performance	Local	Biglia et al. 2021
District Heating	District heating CO_2 emissions are higher than GWHPs; integrating these technologies could favour the transitions towards 4th generation district heating, reducing emissions and increasing renewable energy sources	Urban	Famiglietti et al. 2021
			Pozzi et al. 2021
		Local	Aste et al. 2017
			Aste et al. 2020
Life Cycle Assessment	GHWPs could reduce the environmental footprint of residential buildings, contributing to realize net-zero climate districts	Urban	Famiglietti et al. 2022
		Local	Famiglietti et al. 2023
GWHPs / Air Pumps	GWHPs as cost-savings technologies, especially in cities as Milan where severe air temperatures reduce air pumps efficiency	Local	Aste et al. 2013
Subsurface Urban Heat Island	Underground infrastructures as most relevant factors determining heat accumulation within the shallow aquifer units	Urban	Previati and Crosta 2021a
			Previati et al. 2022
Shallow Geothermal Potential	Shallow aquifer productivity (i.e. water table depth, aquifer transmissivity) as the main factor determining the open-loop thermal potential	Regional	Previati and Crosta 2021b
	Aquifer thickness, porosity, saturation and groundwater advection govern GSHPs geothermal potential		Previati and Crosta 2024

Discussion

Possible connections between surface flood and groundwater management

SUDS could support flood mitigation, favouring rainfall infiltration into the ground. Their efficiency decreases in the case of shallow groundwater (Locatelli et al., 2015; Zhang and Chui, 2019), and close underground infrastructures could suffer stability issues as infiltration is enhanced (Pophillat et al., 2022). Hence, their adoption should be targeted according to local groundwater conditions. The most suitable areas for SUDS implementation are characterised by permeable lithologies and water table depths between 11 and 30 metres (Lentini et al., 2022). Shallow groundwater and clay lenses in western and southern areas of Milan, and a significant number of underground infrastructures in the downtown (Sartirana et al., 2022a), could constrain SUDS application to the northern sectors of the city, characterised by grain lithologies and a water table depth around 10-15 metres. Here, major impacts of surface floods occurred in past stormwater events (Becciu et al., 2018; Raimondi et al., 2021; Taramelli et al., 2022), thus emphasizing the need of adopting these solutions to avoid further negative consequences.

Both surface floods and groundwater rising levels could affect underground infrastructures. In the first case, the water and sediments inrush is rapid but characterised by huge water volumes. Some episodes occurred during storm events in 2010 and 2014 along subway line M3, with four stations that remained closed for ten days (Ravazzani et al., 2016; Becciu et al., 2018), and also along line M5 in 2023 (Fig. 4a). Among the adopted solutions, mitigation measures were designed for subway line M5, where the entrance to some stations is protected by three steps upwards (Becciu et al., 2018) (Fig. 4b), limiting flood impact. Groundwater/underground infrastructures interactions are prolonged but characterised by small amounts of groundwater penetrating underground infrastructures (Sartirana et al., 2022b). Notwithstanding, this can trigger issues over a long period, such as corrosion of foundations (Fig. 4c), especially for non-waterproofed infrastructures. This occurred between Piola and Lambrate stations (subway line M2); to solve this issue, these stations remained closed during summer 2019 for lining works. In both cases, the economic damage is consistent, also due to the interruption of public service.

Integrated urban water management and future perspectives

Historically, open channels were culverted in urban areas to reduce flooding risk (McGrane, 2016). For Milan, this favoured industrial development but caused serious hydrological issues. Sedimentation processes reduce the hydraulic efficiency at some buried sections of the Seveso River (Becciu et al., 2018), as water discharge over a threshold value limits the urban drainage capacity: hence, in presence of intense storm events, water is forced to flow upstream out of manholes (Taramelli et al., 2022). A change of paradigm towards a risk-based approach is needed, considering both structural and non-structural solutions as spatial planning and early warning (Schultz, 2006; Becciu et al., 2018).

The legislative framework adopted for the Lambro River demonstrated the potentialities of bottom-up approaches (Vitale et al., 2020), as solutions promoting collaboration between stakeholders on a voluntary basis and limiting conflicts between upstream and downstream municipalities. Avoiding closed decision-making processes is relevant as, until now, this hindered the implementation of the planned interventions, especially for the Seveso River (Vitale, 2023). The first retention basin was activated only in December 2023 within Parco Nord (Fig. 5b), just a hundred metres before the Seveso is roofed (Fig. 5c). Metropolitana Milanese Spa, the local water supplier that manages the Integrated Water Service (Servizio Idrico Integrato) for the city of Milan, realised the project. An artificial lake, fed by groundwater, will have a recreational role throughout the year, being activated in case of stormwaters to mitigate flood risk, as occurred for the intense rainfall event of May 2024. The commitment of an engineering company highlights the urgent need for coordination between the surface water network, handled by the Public Administration, and the Integrated Water Service management. In fact, this basin could reduce peak flow rates and maintain intact the downstream drainage capacity, not

Fig. 4 - a) water and sediments inrush caused by the stormwater event of 31^{st} October 2023 at Garibaldi subway station; b) mitigation measures to floods at Isola station; c) corrosion of foundations at Sant'Agostino station (subway line M2) caused by groundwater/underground infrastructures interactions. All images have been taken by the authors.

Fig. 4 - a) irruzione di acqua e sedimenti causata dall'evento piovoso del 31 ottobre 2023 presso la stazione di Garibaldi; b) misure di mitigazione dalle inondazioni presso la stazione di Isola; c) corrosione delle fondamenta presso la stazione di Sant'Agostino (linea M2 della metropolitana) causata dalle interazioni tra la falda e le infrastrutture sotterranee. Tutte le immagini sono state scattate dagli autori.

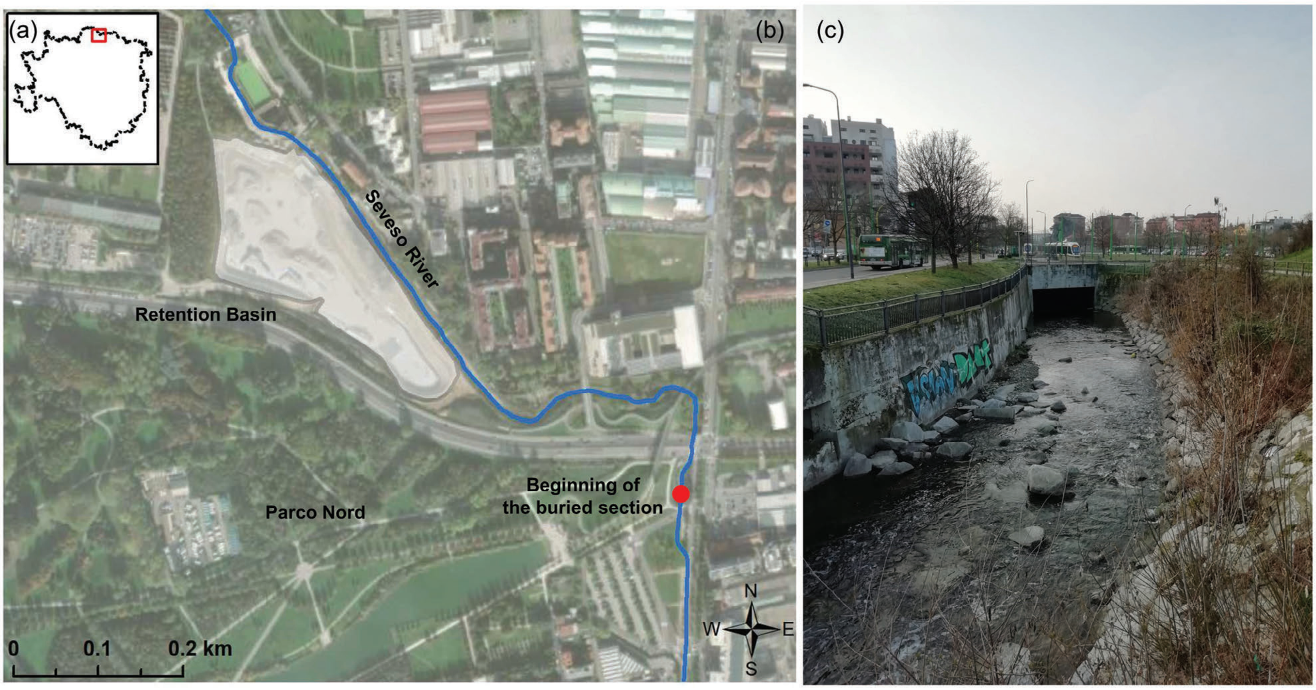


Fig. 5 - a) geographical setting of Parco Nord; b) retention basin and beginning of the buried section of Seveso River, also visible in Fig. 5c). Image c) has been taken by the authors. Service Layer Credits: Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNE S/Airbus DS, USDA, USGS, AeroGRID, IGN and the GIS User Community.

Fig. 5 - a) inquadramento geografico del Parco Nord; b) bacino di ritenzione e inizio del tratto tombinato del fiume Seveso, visibile anche in Fig. 5c). L'immagine c) è stata scattata dagli autori.

overwhelming the sewage network, looking for a balance between environmental and socio-economic protection. The realisation of three further retention basins in the upstream municipalities is an additional solution currently under discussion.

These structural facilities could be supported by adopting further solutions as river restoration techniques, including banks consolidation and re-naturalization to reduce floodable areas, raise water quality and river functionality (Raimondi et al., 2020). Moreover, applying SUDS to enhance infiltration, evaporation or stormwater harvesting and reuse could help to reach the target of hydraulic invariance (Pappalardo et al., 2017; Masseroni et al., 2019; Raimondi et al., 2023), defined by the PGT. Modern buildings such as Bosco Verticale were designed in Porta Nuova District following these principles.

The administrative cooperation desired for flood mitigation is also a relevant measure for groundwater management. An inter-institutional framework grouping public administrations, urban planners, water stakeholders and infrastructure developers, supported by the Universities, could guarantee a proper management of all the underground resources (Radutu et al., 2022). In this sense, groundwater consideration in urban policies is increasing: the first floors of some new buildings are used as car parks (Sartirana et al., 2022b), not designed underground, to avoid groundwater/underground infrastructures interactions in the western areas of the town. Defining targeted pollution management plans (Azzellino et al., 2019) and emerging contaminants monitoring in drinking waters (Riva et al., 2018) to establish guideline values for regulatory aims demonstrate groundwater quality consideration in planning policies. As for groundwater temperature, a technical documentation is needed to install GWHPs plants, considering the possible interactions with surrounding plants and the effects on the aquifer thermal plume (Berta et al., 2024), highlighting the effort of developing an integrated management. In the next future, the focus could be moved also to evaluate temperature-induced impacts on the hydrochemistry and the microbial communities of the system (Bonte et al., 2013). The shallow aquifer is not exploited for drinking needs, but these analyses could support a global sustainable management of the resource.

A possible urban transformation involves the daylighting of the ancient Navigli canal system, to fully restore the original scheme. The inner ring was roofed in 1929: nowadays, only three Navigli canals (Grande, Pavese, and Martesana) (Fig. 6) are still active. The project involves landscape, historical, architectural but also hydraulic restoration (Boscacci et al., 2017; Sibilla et al., 2017). This latter could also interest surface flood and groundwater rising levels management. Regarding flood mitigation, disconnecting Naviglio Martesana from the culverted section of Seveso River could guarantee a safe stormwater removal, moving peak flow rates from Seveso to Lambro River through the Cavo Redefossi (Sibilla et al., 2017). In this way, uncontrolled discharges of poor-quality water to the canals would be avoided. The flow rate of Naviglio Martesana will be the main water source feeding the inner ring, allowing canal navigability. Additional flow rates, also increasing canals water quality, could be discharged by groundwater extracted to control water table rising, also using

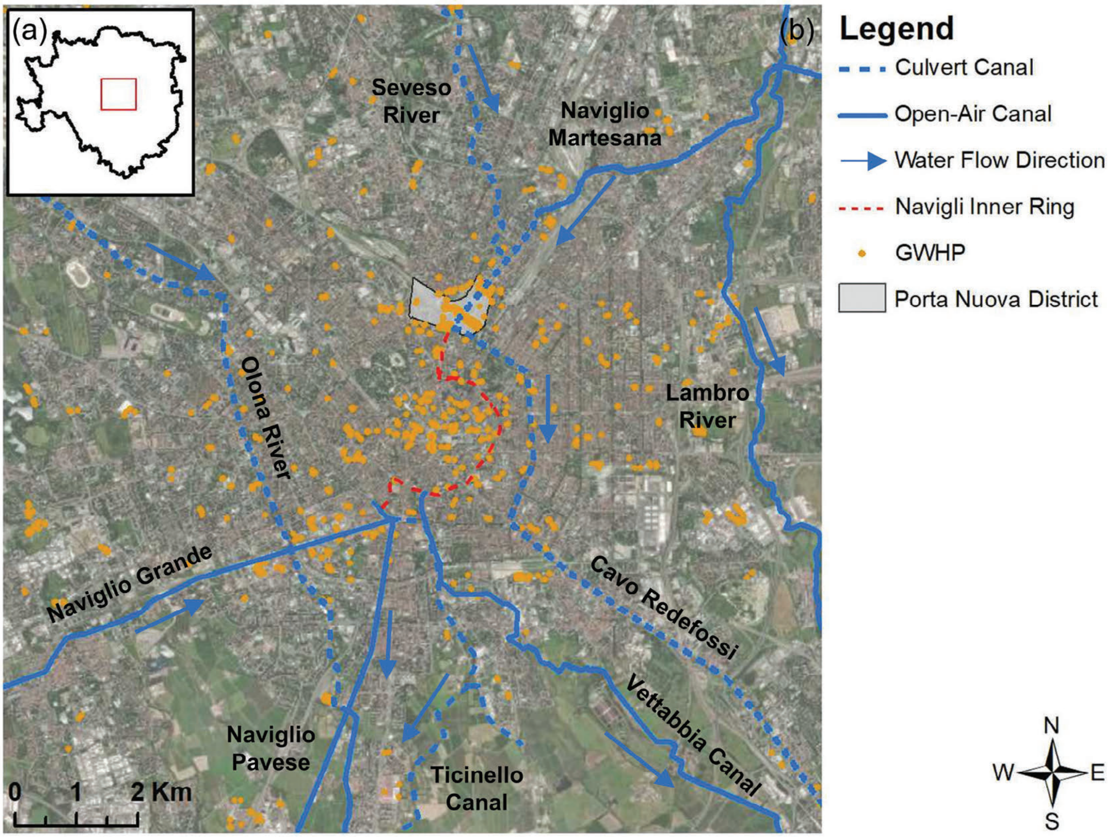


Fig. 6 - a) geographical setting of Navigli inner ring; b) surface water flow hydrographic network and relation to the Navigli inner ring.

Fig. 6 - a) inquadramento geografico della cerchia interna dei Navigli; b) rete idrografica delle acque superficiali e relazione con la cerchia interna dei Navigli.

GWHPs plants around Porta Nuova district (Fig. 6), mostly designed only through extraction wells. Further heat pumps could be installed to feed close buildings, withdrawing water directly from the canals, as their temperatures will be relatively constant throughout the years, demonstrating the energy potential of the project.

Getting the most out of data for urban water management

A large amount of data is available in urban environments, where multitude of interests are present (Parriaux et al., 2007). Analysing this information could guarantee a sustainable management of all these resources. Sometimes, further information could reduce data uncertainty, providing better support for the decision-making process. This occurred for rainfall-runoff modelling: the non-linearity of the hydrological processes taking place at urban scale promoted the investigation of further strategies to support civil protection early warning mechanisms.

Buildings vulnerability to floods was analysed by collecting information on the residential sector also using Open Source Databases (Taramelli et al., 2022). The presence of basements increased vulnerability, limiting the response capacity to stormwaters. The subsurface occupation of private buildings was also detected using the Topographic Database as a primary source of information to create a 3D geodatabase for underground infrastructures and evaluate their interactions with rising water table levels (Sartirana et al., 2020). Hence, Open-Data resulted a valuable source for buildings information (Figueiredo and Martina, 2016), thus supporting risk decision-making both for surface flood and groundwater issues.

Groundwater/underground infrastructures interactions have been investigated through numerical modelling (Gattinoni and Scesi, 2017; Colombo et al., 2018; De Caro et al., 2020a; Sartirana et al., 2022b), 3D geodatabase (Sartirana et al., 2020) and data-driven techniques (Sartirana et al., 2022a). The same underground infrastructures emerged as critical, proving the reliability of these techniques. Data-driven techniques as CA were applied not only to support underground infrastructures management (Sartirana et al., 2022a), but also for groundwater qualitative analyses (Azzellino et al., 2019) to define DBPLs and identify the main factors influencing groundwater geothermal potential (Previati and Crosta, 2021a). This proves the accuracy of these tools in dealing with large datasets, characterising the spatial and temporal variability of different groundwater patterns (Bosserelle et al. 2023). As for quantity (Sartirana et al., 2022a) and quality (Azzellino et al., 2019) aspects, data-driven methods suggested that groundwater should not be handled homogeneously within the domain, as different hydrogeological and hydrogeochemical processes can take place at small spatial scales, requiring targeted solutions for an efficient water management (Chaudhuri and Ale, 2013). Currently, time and economic reasons are determining a progressive downsizing of the Milan groundwater monitoring network. To keep gaining knowledge about groundwater processes, a minimum size of data collected is required; as for groundwater quantity, at least two measures per year are useful to detect seasonal processes. A strict collaboration between Universities and stakeholders could be a valuable solution to optimise the monitoring network, eliminating data redundancy, looking for a compromise between cost minimization and prediction accuracy (Meggiorin et al., 2024).

Conclusions

This work investigated, through a state of the art analysis, two topics of urban water management for Milan Metropolitan Area: surface floods mitigation and groundwater management (quantity, quality, and temperature). In the next future, both researchers and stakeholders could consider this review as an updated reference, hopefully supporting a sustainable management of the resource. This literature analysis evidenced that:

- A lack of coordination between stakeholders, also due to conflicts between upstream and downstream municipalities, slowed down the transition towards a risk-based approach, especially for the Seveso River. A bottom-up approach could favour the implementation of the structural measures needed, as the first retention basin activated in December 2023.
- Structural measures for flood mitigation should be supported by non-structural measures such as early warning systems and SUDS. These latter should be located where the water table is relatively deep, to avoid efficiency losses and not impact underground infrastructures.
- Groundwater themes should be integrated with urban planning to properly handle all the underground resources. Groundwater/underground infrastructures interactions are progressively managed with this approach. Groundwater quality of the shallow aquifer resulted severely impacted by different PS and NPS sources; these were identified integrating numerical modelling and data-driven methods, highlighting the importance of targeted management plans. As for groundwater temperature, the shallow aquifer has a significant geothermal potential; hence, further GWHPs could be installed, managing their relation carefully to avoid reducing their efficiency, also considering their adoption to limit water table rising, without affecting groundwater quality.

In the next future, the stakeholders should consider the adoption of site-specific measures, through an enhanced cooperation between different government levels not only for Milan but also elsewhere, as climate change and urbanisation are presumably becoming a constant threat for urban areas in the coming years. Only in this way an integrated administration of the urban water resource could be guaranteed, considering both flood risk and groundwater management.

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Chiara Zanotti: Methodology, Visualization, Writing - Review & Editing.
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