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PAPER

Review: Urban groundwater issues and resource management, and their roles in the resilience of cities

Francesco La Vigna[1]

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Abstract

The relationships between cities and underlying groundwater are reviewed, with the aim to highlight the importance of urban groundwater resources in terms of city resilience value. Examples of more than 70 cities worldwide are cited along with details of their groundwater-related issues, specific experiences, and settings. The groundwater-related issues are summarized, and a first groundwater-city classification is proposed in order to facilitate a more effective city-to-city comparison with respect to, for example, the best practices and solutions that have been put in practice by similar cities in terms of local groundwater resources management. The interdependences between some groundwater services and the cascading effects on city life in cases of shock (e.g., drought, heavy rain, pollution, energy demand) and chronic stress (e.g., climate change) are analyzed, and the ideal groundwater-resilient-city characteristics are proposed. The paper concludes that groundwater is a crucial resource for planning sustainability in every city and for implementing city resilience strategies from the climate change perspective.

Keywords Urban groundwater · sustainability · urban subsoil dynamics · groundwater city clustering

Introduction

Groundwater is the hidden part of the hydrologic cycle and its being hidden is particularly significant in large urbanized sectors where the few evident groundwater-related phenomena, such as springs or groundwater-fed streams, are usually covered or buried by anthropogenic deposits (Peloggia 2018) and infrastructure. Thus, flow and transport processes affecting urban groundwater are not essentially different from those affecting groundwater in rural contexts, but the time and space scales involved are significantly different (Fletcher et al. 2007; Vazquez-Sune et al. 2000).

As stated by Coaffee and Lee (2016), “this century is the "century of cities", where rapid urbanization and more significant global connectivity present unprecedented urban challenges and risks in urban areas, making them increasingly vulnerable to a range of shocks and stresses”. Moreover, urbanization is a worldwide trend, with more than 55% of the world's population currently living in cities, reaching 70% in Europe (UN 2019); thus, the urban water cycle is a crucial issue for ensuring the supply of safe (good quality) water, sanitation and correct drainage systems for so many citizens. Furthermore, human activities such as land-use change, substantial withdrawals, and wastewater discharge can have a greater impact on groundwater systems and hydrogeology than climate change, causing changes in the qualitative and quantitative state of both surface water and groundwater. Consequently, urban water and groundwater management poses not only scientific but also technical, socio-economic, cultural, and ethical challenges (Afonso et al. 2020).

In the interests of adequate and long-term groundwater protection, urban planners and lawmakers should fully integrate an understanding of the subsoil into the deliberation/decision-making process. Where appropriate, they should take into account the hydrogeological setting, the groundwater flow dynamics, and the extended time frames over which impacts of land use on groundwater can occur (Howard 1997).

As stated by Lerner (1997), “urban groundwater could be both an asset and a problem: it could be an asset because of its value for water supply for human consumption, and several uses (industrial, irrigation, fire prevention), it could be

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✉ Francesco La Vigna
francesco.lavigna@isprambiente.it

[1] Geological Survey of Italy – ISPRA, Rome, Italy

a problem because of the health risk from pollution, but also because of the interference with urban infrastructure". Always according to Lerner (1997) overexploitation under the city area determines the lowering of the water table and subsidence issues; on the other hand, in the later stages of city development, the abstraction rates decrease determining the rising of the water table that can flood buried infrastructure. However, the groundwater resource offers unique advantages compared with other types of water resources. It may be more widely available, less vulnerable to climate change, of superior quality, and cheaper to develop and distribute (Sharp Jr 1997).

There are three main functions of urban groundwater management: water supply provision, wastewater disposal, and engineering infrastructure development and maintenance. According to Morris et al. (1997), "the key to sustainable city development is reconciling these three legitimate but different and potentially conflicting functions". Moreover, not all cities can count on a local water supply or local wastewater treatment and thus the effects of associated water management strategies can impact much wider water catchment sectors even many kilometers away from the city area.

As stated by Schirmer et al. (2013), "the issues concerning the management of urban water resources are not new; in fact the cities need a reliable supply of clean drinking water on the one hand, and on the other hand, contaminated urban groundwater and wastewater have to be treated, and stormwater has to be managed. These necessary tasks have substantial overlap with 'integrated urban water management' schemes". This approach can also be defined with the concept of "One Water" introduced by Howe and Mukheibir (2015), which describes this comprehensive and long-term approach to community-based water management. One Water considers the urban water cycle as a single integrated system. A One Water approach recognizes all urban water supplies as resources – surface water, groundwater, stormwater, and wastewater (Howe and Mukheibir 2015) with a holistic sense, as part of cities' resilience.

The resilience of cities has recently become a persistent item in the agenda for many city governments (Leitner et al. 2018). In the last years, many non-governmental organizations (NGOs) have launched different programs for cities and megacities to foster processes that incorporate resilience strategies (Da Silva and Morera 2014; Day et al. 2018), and many city best-practice exchange workshops have been organized. The term "urban resilience", after Meerow et al. (2016), has been described as "the ability of an urban system and all its constituent socio-ecological and socio-technical networks across the temporal and spatial system, to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change, and to transform systems that limit current or future adaptive capacity quickly".

Coaffee and Lee (2016) synthesized and described the main terms or keywords that underlie cities' resilience as follows, also referring to other authors:

"*Cyclicality* is at the base of every resilience approach due to the nature of cyclical processes involving several overlapping stages;

Redundancy is the co-existence of diverse options fulfilling the same purpose and ensuring functionality in the event of the failure of one of them; it can also be attained through the identification of synergies amongst seemingly diverse realms or sectors, which in turn prompts the design of buildings, spaces, and infrastructure that can be used (or can be adapted to be used) in multiple ways (Caputo et al. 2015);

Adaptation is a critical concept that captures the capacity of a system to learn, combine experience and knowledge, and adjust its response to changing external drivers and internal processes (Folke et al. 2010);

Mitigation is the sum of those actions to reduce or eliminate long-term risk to people and infrastructure from a range of stresses and their effects;

Preparedness is mainly focused on anticipating events and creating a response capability and better *awareness*, both for city managers and city technicians on one hand and for citizens in the other;

Response is the phase that involves action taken during and immediately after a shock event occurs, focusing on minimizing damage and allowing a system to re-establish base functionality as rapidly as possible;

Recovery is the phase seeking to utilize the attributes of responsiveness and involves short-term or long-term phases of rebuilding and restoration to return to normality or a new (better) normality, learning from previous errors (reflexivity)."

The methodology for achieving the assessment of cities' resilience and its enhancement often follows the same path, even if with different nuances; a city's aspects are evaluated through a holistic approach, interdependences and cascading effects of each measured aspect, and a final resilience strategy is proposed following the political vision.

This paper reviews the relationships between cities and groundwater and discusses the interdependences with respect to other aspects, the related cascading effects, and thus the potential resilience value of the in-depth knowledge and correct management strategy.

Review method

There are several important review works in literature that address the matter of "urban groundwater". This work did not aim to refresh these exhaustive papers since it sees the same matter from another perspective. The review activity started by reading the handy compendiums edited by Chilton et al. (1997), Chilton (1997) and Howard (2007) and furtherly took into consideration other review papers, such as the works of Lerner (2002), Herringshaw (2007) and Schirmer et al. (2013). After the review papers, many more specific works on peculiar issues or city case studies were analyzed. The structure of this paper is thus organized firstly to list as many urban groundwater issues as possible, secondly to cluster cities from a hydrogeological point of view, and then to summarize as many groundwater-related best practices implemented by cities as possible. The review discussion is approached by looking at the "resilience value" that a city can achieve through the virtuous management of local groundwater resources. Fig. 1 shows all the 73 cities cited within the text (reported in a table in the Appendix Table 5 as well as in a factsheet available in electronic supplementary materials - ESM) as examples of groundwater-related issues or characteristics or best practices.

Urban exponential development and sprawl vs. abandonment of rural areas, and the change of water demand

On a global scale, more than half of the world's people live in urban areas today (UN 2019) and out of this urban population, two out of three are in developing countries. By 2025, four urban dwellers will be in developing countries for each one in the developed world (Vairavamoorthy et al. 2008).

Urbanization is a complex process of change of rural lifestyles into urban ones, and it has shown almost exponential growth since the end of the 19th century (Antrop 2004). City populations eat enormous amounts of food which they import from the countryside, often far away. Megacities alone import as much water as what crosses national borders in all the international food trade (Varis et al. 2006); in addition, it should be considered that people who once lived in rural villages, where a reliable water supply was not widely available, but moved to the cities, significantly increased their contribution to the general water demand. The people in urban and urbanizing areas require water, and groundwater supply issues stem from these demands (Sharp Jr 1997). As stated by Foster et al. (1999), "the provision of water supply, sanitation, and drainage are vital elements of the urbanization process which often coexists with the prevalence of informal groundwater abstraction; in fact, significant differences in the development sequence exist between higher-income areas, where it is (or it should be) generally planned, and lower-income areas of developing nations, where informal settlements are progressively consolidated in urban areas with rapid growth of unregulated/uncontrolled groundwater supplies".

"The urban growth characterized by an excessive increase in urban land uses, decreasing urban density, and a spatially dispersed distribution of households and economic functions" is defined by Siedentop and Fina (2012) as 'urban sprawl'. According to Stevenazzi (2017), urban sprawl significantly impacts the environment, the social structure and the economy, and has the following effects on groundwater: "(a) the increase of non-point sources of contamination related to urban activities; (b) the reduction of the capacity of soil to act as a filter for contamination sources; (c) the decrease of permeable surface area, which influences the quantity of groundwater recharge; and (d) changes to surface water and groundwater interactions."

In many fast-developing cities informal settlements grow on marginal land or in periurban districts, thus, the effect of urban water supply and wastewater disposal will consequently interest also the surroundings. As a consequence, as highlighted by Morris et al. (1997), "water supplies originally obtained from shallow underlying aquifers may no longer be sufficient, either because the available resource is too limited or because of quality deterioration from pollution and thus, the extra water resources required will either be tapped from deeper aquifers, or more often, will be drawn from aquifers or surface water bodies in the city hinterland area". According to Foster et al. (2020), "in-situ residential self-supply from groundwater is a 'booming phenomenon' in numerous sub-Saharan Africa cities, which are experiencing unprecedented rates of urban population growth, and widely represents a significant proportion of the water received by users".

Sharp Jr (1997) stated that "solutions for increased water demand must follow one or more of the three following options: reduce water demands, use available waters more efficiently or increase water supplies". As it is not possible to limit the population growth, decreased demand could be achieved by publicly promoting water consumption reduction and sustainable use, while several actions can be put into practice to achieve water conservation by reducing water-main losses. When increasing water supply is not sustainable or possible, the objectives can be met presently by conjunctive use of secondary water sources such as harvesting rain and stormwater or utilizing non-potable waters.

Groundwater awareness in cities

When a city administrator wants to increase the city's resilience, there are usually many actions that can be undertaken or developed, both structural and non-structural. Structural actions are those which need works in order to obtain the result (e.g., a wall to protect a road from a landslide); non-structural actions are those that achieve their desired effects directly by influencing people behavior (e.g. a public campaign on rising awareness of landslides). Usually, "structural" actions are very effective and involve a lot of time and money to be implemented, while "non-structural" actions are often implemented at a meager cost but require substantial interdisciplinary and inter-institutional work, often with the involvement of the population itself. The first "non-structural" resilience action that can be implemented usually is to raise citizen awareness. This action is even more relevant to the situation involving groundwater because, in reality, groundwater is usually not visible and its concept is often more challenging to understand for most people. Several instruments allow citizen groundwater awareness to increase and are listed as follows.

Groundwater monitoring

Monitoring groundwater and surface water resources is a critical step in improving the urban water system and reducing water use and degradation., but it is also a very effective instrument to increase the citizens' awareness; the saying "you cannot manage what you do not measure" applies well to groundwater and urban groundwater management (Bonsor et al. 2017).

Furthermore, different groundwater management approaches are used in metropolitan areas across the world. As a result, hydrogeological monitoring is required for a variety of applications, including: preserving groundwater resources; establishing groundwater protection zones in newly urbanized areas; analyzing groundwater potential; recognizing groundwater vulnerability; estimating the recharge caused by sewer and pipe leakage; documenting the historical evolution of urban groundwater systems. The challenge is to identify the cause and time of groundwater changes. Appropriate monitoring networks need to be designed for the stated purpose, e.g., bringing about the distinction between shallow and deep urban aquifers. Moreover, as sometimes city catchment surfaces are subject to frequent changes, it is very important to precisely define the elevation of monitoring stations, in order to avoid poor definition of the groundwater flow gradient (La Vigna and Baiocchi 2021).

Not all cities have a dedicated groundwater monitoring network, even if the number of drillings and water wells is typically high and the distribution usually is wide. In some cases, instead, city-scale groundwater monitoring is a reality. For example, Miami (Florida, USA), has a real-time monitoring network managed by the US Geological Survey (Prinos et al. 2002). In the Beijing city area (China), a monitoring network has been working since the 1960s and, despite some periods of not working, the network data coming from hundreds of wells allow one to see the water table behavior very well during the monitored periods (Zhou et al. 2013). To monitor changes in the quantity of groundwater resources and their quality, the metropolitan government of Seoul (South Korea) established a local groundwater monitoring network in 1997 consisting of 119 monitoring wells (Lee et al. 2005). Rome municipality (Italy) has recently organized its irrigation wells as part of the city monitoring network (La Vigna et al. 2015b) and detailed the monitoring activity in some heritage sites (Mastrorillo et al. 2016). Other examples are the monitoring network of Cardiff (UK), which is monitoring the groundwater levels and temperature also to control groundwater thermal variations due to shallow open-loop ground-source heat pumps (Patton et al. 2020), the network of the City of Bucharest (Romania) (Gaitanaru et al. 2017), and that of Glasgow (UK). In general, Dutch and German cities have monitoring networks, with a significant development in Amsterdam (The Netherlands), with more than 2500 monitoring stations bimonthly measured (Bonsor et al. 2017), and Munich (Germany), with almost 500 monitoring wells (Menberg et al. 2013).

City-scale hydrogeological maps and 3D numerical models

More detailed hydrogeological mapping is required in urbanizing areas to reduce setting uncertainties, to enable groundwater utilization and sustainable management, and to make groundwater more visible for non-experts. This is especially critical when various water supply options are considered. In addition, detailed hydrogeological maps are crucial for solving urban planning issues (Sharp Jr 1997) e.g., to identify areas suitable for projects that could interact with aquifers such as stormwater infiltration or industrial plant locations. Some examples of cities having specific official city-scale hydrogeological maps are Rome (Italy) (La Vigna et al. 2015c; La Vigna et al. 2016), Moscow (Russia) (Osipov 2015), Bucharest (Romania) (Gaitanaru et al. 2013), Porto (Portugal) (Afonso et al. 2007a).

Moreover, in order to better understand and manage all the interactions between groundwater, the environment, and underground structures (Attard et al. 2016b), and in order to manage provisional scenarios of groundwater dynamics, three-dimensional (3D) city-scale numerical models have been built sometimes, as done (e.g.) for the cities of Bucharest (Romania) (Boukhemacha et al. 2015; Gogu et al. 2015), Paris (France) (Thierry et al. 2009), Lyon (France) (Attard et al. 2016a), Milan (Italy) (Colombo 2017; Gorla et al. 2016) and London (UK) (Jones et al. 2012).

According to Schirmer et al. (2013), “since only part of the groundwater system can be measured, water and contaminant flow and transport models are indispensable; the urban groundwater compartment interacts closely with the unsaturated zone, sewage systems, and surface water.” Groundwater models often must be coupled to the other compartments holistically. Such models are defined as IUWS (integrated urban water systems) models (Schirmer et al. 2013).

Local or extra-city-boundary water supply

In many urban and peri-urban areas, there are cases in which local aquifers cannot meet the quantity and quality of water needs of the growing population. Thus, extensive supply waterworks have been developed, and local aquifers have been progressively abandoned except for marginal uses, losing or downgrading their considerable potential, at least as an essential emergency water service (Custodio 1997). According to Morris et al. (1997) the impact of a city on local groundwater can be progressive and hand in hand with urban development. A city is not static; it grows and

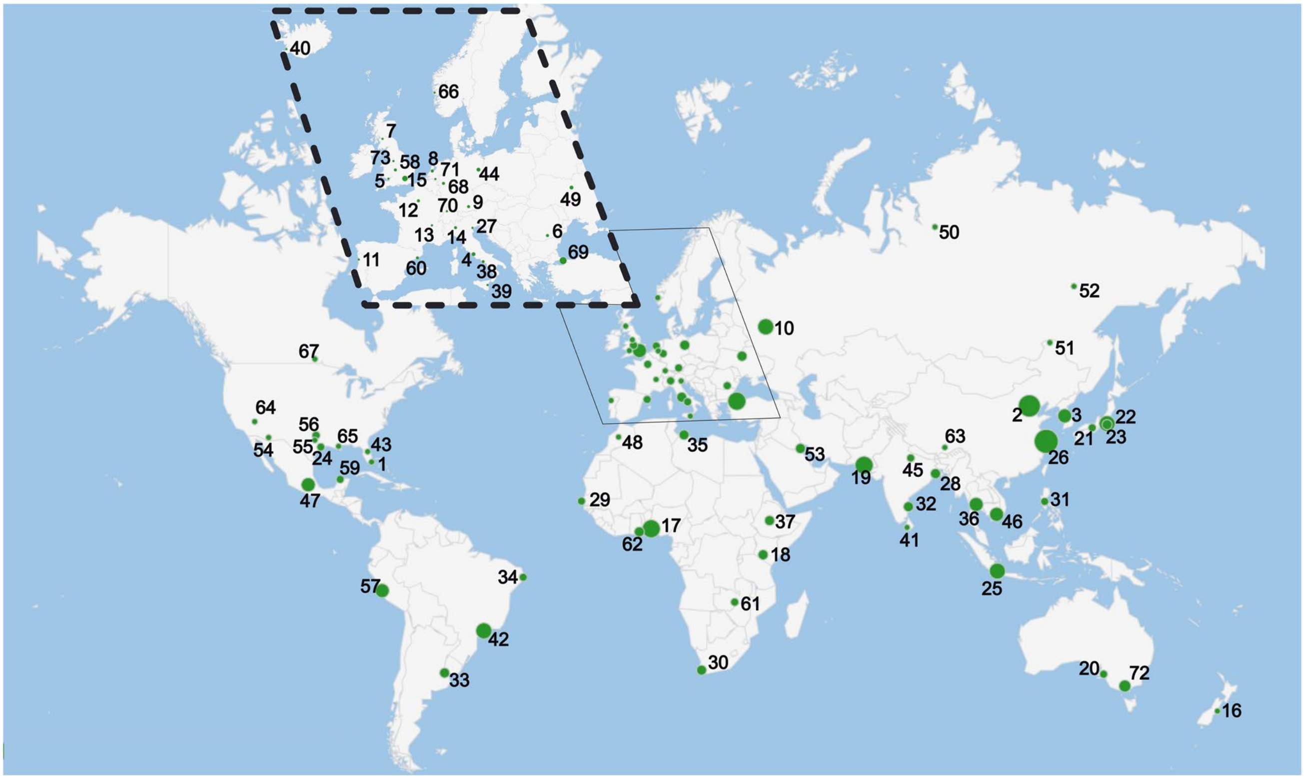

Fig. 1 Locations of cities cited in the text; the labels correspond to the citation order within the text, while the symbol dimension is proportional to the number of inhabitants (base map from Google Maps). A list of cited cities with relative state and city typology is reported in the Appendix Table 5 and in the electronic supplementary material (ESM)

changes with time, and its effects on the groundwater system too (Shanahan 2009). For cities that supply from local groundwater, at the beginning of the city growing period, the affected water table is normally below the city area with a wide cone of depression due to the many supply wells; when the city expands the water supply moves towards the peri-urban field and the water table in the central area starts to rise due to the local withdrawal stopping (in response to changes in the local water demand and/or changes in the local groundwater quality), and due to the "urban" recharge as well. In some cases, and with several historical examples, the water supply catchment has moved outside the city boundaries by several kilometers, affecting other catchments and basins, and water is brought into the city through important aqueducts (Angelakis and Mays 2014).

In most cases where groundwater is the main or sole source of water supply for the municipality, e.g., for the city of Christchurch (New Zealand), (Mudd et al. 2004), and where urban abstraction wells are mainly located within city limits, the groundwater withdrawal will significantly exceed the long-term rate of recharge. Moreover, where the local abstraction is mainly focused on high-quality and deeper groundwater, substantial volumes of shallow more vulnerable groundwater will often be available and suitable for many uses (Morris et al. 1997).

In many cities where the municipal water supply service is (or has been) inadequate, many private water wells have been drilled over time. According to Foster and Hirata (2011), “the growth in private urban groundwater use is not restricted to cities with ready access to high-yielding aquifers, an it is often even more pronounced where minor shallow aquifers occur”: for example, this happens in Lagos (Nigeria), one of the world's five megacities, where the majority of the population uses wells (either boreholes or hand-dug) for drinking and domestic purposes (Adelana et al. 2008), or in Nairobi (Kenya), where private drilling by commercial, industrial and multi-residential users grew from around 1990 and the number of active water wells is believed to exceed 5000, contributing to the general local groundwater resource depletion, with water levels falling 50-100 m in the past 30 years (Foster et al. 2019).

The “world” of shallow urban groundwater

Commonly, shallow urban groundwater is frequently overlooked or ineffectively managed, in large part because it is often poorly understood and studied. The urban shallow aquifers have, however, an essential role in city life: providing several ecosystem services in the cities, including maintaining healthy urban river flows; supporting groundwater-dependent ecosystems and habitats; attenuating some pollutants; mitigating the impacts of extreme rainfall events, welcoming the infiltration water through sustainable drainage systems; providing water for urban tree roots (Dochartaigh et al. 2019).

On the other hand, the shallow urban underground is an intricate network of tunnels, conduits, utilities, and other buried structures comparable to a natural karst system, except that this "urban karst" is generated much more rapidly (Garcia-Fresca 2007); the relationship between this network and the shallow aquifer systems below cities is sometimes a challenge and a mutual threat. For this reason, in some cities, such as (e.g.) Glasgow (UK) (Dochartaigh et al. 2019) or Rome (Italy) (Clausi et al. 2019), particular importance is being given to understanding shallow aquifers better. Furthermore, in some cities where thick strata of anthropogenic deposits, or artificial ground (Ford et al. 2010), is widely present, shallow groundwater is usually flowing in these anthropogenic aquifers.

The citizens' groundwater awareness – making the invisible visible

Where several actions related to groundwater use, monitoring, protection, and eventual abstraction reduction are contemplated, as noted by Briscoe (1993), "it will be technically and economically more feasible if the policy can be implemented through dissemination activities or some form of a water-user group organized within the community or municipal framework" in order to increase citizen groundwater awareness. According to Tanner et al. (2009) climate change in urban areas affects the poorest and most vulnerable, first disproportionately and most severely, thus, their integration in decision-making and policy processes is crucial for building climate resilience in order to improve the living conditions for those living in informal settlements or in exposed locations.

As in cities the water consumption is normally very high, they are very good laboratories to promote policies to reduce water footprint. "Simple" demand-reduction tools, such as suitable pricing, rainwater collecting, or wastewater recycling, can have huge impacts when broadly implemented and enforced on families and industry (Engel et al. 2011). Involving marginalized groups in management solutions and implementation is crucial, as the success of Karachi's *Orangi Pilot Project* in Pakistan demonstrates (Orangi Pilot Project 1995). This project, as reported by Engel et al. (2011), "gave residents in poor communities the resources and engineering expertise to help solve their environmental challenges. An NGO started the project in the 1980s in Orangi Town, a cluster of low-income settlements in Karachi (Pakistan) with a population of 1.2 million. The project's initial focus was sewer improvements. Residents constructed sewer channels to collect waste from their homes, and these were then connected to neighborhood channels, which ultimately discharged into the municipal trunk sewer".

Sometimes the involvement of citizens is formal and aims to increase the base knowledge (La Vigna et al. 2017), sometimes creative and interactive instruments have been proposed to the citizens, such as visioning exercises: for example, the *London 2036 gaming model* (Wiek and Iwaniec 2014) was presented to a sample of 15,000 people by way of questions on water resources, housing and transport. In this activity, as reported by Bricker et al. (2017), "each participant was provided with a forecasted future for London (UK) unique to their answers, which also evaluated water availability concerning some actions to be implemented, thus allowing participants to reflect on the implications of their responses. As well as providing participants with individual feedback on future scenarios, results from the gaming models provide an informal insight to assess the public acceptance of new initiatives and policy decisions for London".

Student involvement has been tested (e.g.) in Adelaide (Australia) with the *Groundwater Watch summer program* in 1993/1994. In this experience, student volunteers from 32 South Australian high schools participated in a summer vacation groundwater education and sampling program, which provided valuable quality-assured data. In addition, this experience resulted in an increased awareness of urban groundwater by students, bore owners, and the community via the considerable media attention the program received (Dillon and Pavelic 1997).

In other cases, citizens have been involved in providing an emergency water supply system to use in case of necessity. An example is a Japanese case put into practice after the Hanshin-Awaji earthquake (Mw 7.3) in 1995, which caused water supply interruption for around 1,270,000 households and many hospitals (Tanaka 2008). Despite this shock caused by the earthquake, it was possible to pump groundwater from several wells immediately after the earthquake, due to their resilience against the seismic effects, thus, a registration system of citizen-owned wells was established in 1996 in Kobe. Within the next two years, 517 suitable emergency wells were registered, equipped with a hand pump, and their location entered on maps. Based on the Kobe experience, many municipal and local Japanese governments have established similar emergency water-well systems to be used as safe water sources in an emergency: the Tokyo Metropolitan Government with 2,769 emergency wells in 23 districts, and the Yokohama City, with 3,517 registered wells, where water quality checks were conducted monthly to the same analytical standard as for municipal supply water (Guo et al. 2011).

Groundwater awareness is crucial for the interpretation of urban groundwater management for a vital urban groundwater monitoring network. In addition, operating public groundwater observation wells can help make groundwater visible, and displaying the results via the internet increases the visibility (Bonsor et al. 2017).

Groundwater city classification

It is always challenging to try clustering cities, but there are very peculiar hydrogeological settings and/or climate contexts, and/or geographical locations, that determine specific groundwater flow characteristics, and thus, it is possible to propose a sort of general classification. Not all climate contexts are considered, but just those having a clear connection with groundwater dynamics. Many cities are not easily attributable to a single category but a combination of the following.

A resume of the following proposed groundwater city classification is available as Electronic Supplementary Materials (ESM).

Coastal, lagoon, and delta groundwater cities (CGC - LDGC)

Coastal, lagoon, and deltaic cities are hydrogeologically in connection with the “zone of transition” where the seawater/freshwater interface is below the ground surface (Fig. 2).

Depending on their geological setting, coastal and lagoon cities can experience different groundwater-related issues. Coastal and deltaic cities located on soft sedimentary soils, such as (e.g.) Huston (USA), Jakarta (Indonesia), Shangai (China), Venice (Italy), and Kolkata/Calcutta (India), may be subjected to severe subsidence related to overdraft and this can also contribute to an increase in the local coastal hazards. Overexploitation of aquifers under coastal cities or interior cities located near the coast can also cause saltwater intrusion. This phenomenon is significant for cities on oceanic islands (Sharp Jr 1997). Examples of cities affected by seawater intrusion are Dakar (Senegal) and Cape Town (South Africa) in Africa (Adelana et al. 2008), Manila (Philippines), Chennai (India), and Jakarta (Indonesia) in Asia (King 2003), and Buenos Aires (Argentina) (Engel et al. 2011) and Recife (Brazil) in South America (Montenegro et al. 2006). In Tripoli (Libya), seawater intrusion steadily increased from 1960 to 2007, when potable water was available from the local aquifer; since 1999, a loss of 60% in well production in the upper aquifer has been observed (Alfarrah and Walraevens 2018). Some cities, such as Bangkok (Thailand), are suffering both aquifer compaction-related subsidence (IGES 2007) and seawater intrusion (Foster et al. 2019).

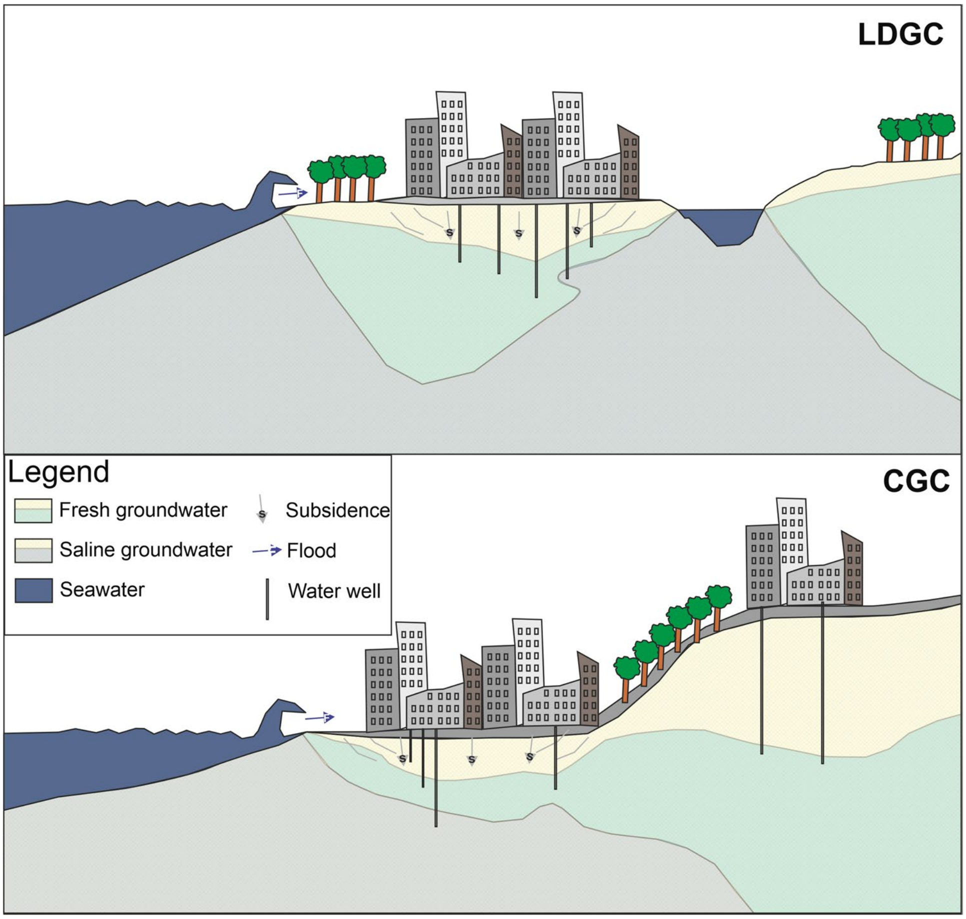

Fig. 2 Coastal and lagoon/delta groundwater cities conceptualization – These kinds of cities are in correspondence with the “zone of transition” where the seawater/freshwater interface is below the ground surface. When these cities are located on soft sedimentary soils, they can be subjected to severe subsidence as a result of overdraft and this can also contribute to an increase in the local coast-related hazard

Delta cities can also be impacted by saltwater intrusion through the main river mouth, typically during the dry season when the river discharge rate is lower. This phenomenon can also generate a change in saltwater/freshwater equilibrium in the groundwater, as occurring (e.g.) in Shangai (China) (Engel et al. 2011); along the Tiber River in the coastal sector of Rome (Italy) salt-wedge intrusion can occur during periods of the high river discharge rate, mainly due to the wind effect contributing to the increase the local river and aquifer salinity (Manca et al. 2014).

Volcanic groundwater cities (VGC)

Depending on the volcano's typology, cities located on, or close to, volcanic districts are characterized by aquifers with a particular setting usually influenced by the volcanic depositional activity, with frequent abrupt changes in permeability (Fig. 3). Moreover, thermalized and mineralized groundwater is frequently found, even if the volcano is quiescent or no longer active, and the presence of natural background contaminants is possible in these contexts due to the volcanic nature of the rocks. For example, Addis Ababa (Ethiopia) is dominated by volcanic materials of different ages and compositions, and the deepest wells reach a thermal aquifer in the center of the city (Adelana et al. 2008). Several important Italian cities grew up in a volcanic context: Rome is located between two volcanic districts (Colli Albani Volcano and Sabatini Volcano), Naples is between the Phlegrean Volcanic Fields and the Somma-Vesuvius Volcano, and Catania is on the side of Mt. Etna Volcano. The groundwater of these cities is hydraulically, thermally, and chemically influenced by the volcanic presence: in Rome, several aquifers are sustained by tuff products acting as aquitard and groundwater is locally thermalized with temperature values reaching 22°C (La Vigna et al. 2016; Mazza et al. 2015); in Naples, the CO_2 upwelling along the faults increases the HCO_3 content in groundwater and also determines the solution of Fe and Mn in some aquifers, sometimes modifying the natural relationship between freshwater and saltwater and creating a natural seawater intrusion (Corniello and Ducci 2019); in Catania, the principal aquifers are inside vast lava flows, which are very productive due to their high degree of secondary permeability (Ferrara and Pappalardo 2008).

In Reykjavik (Iceland), most households are heated with geothermal water or geothermally heated freshwater from district heating services that use advanced technologies

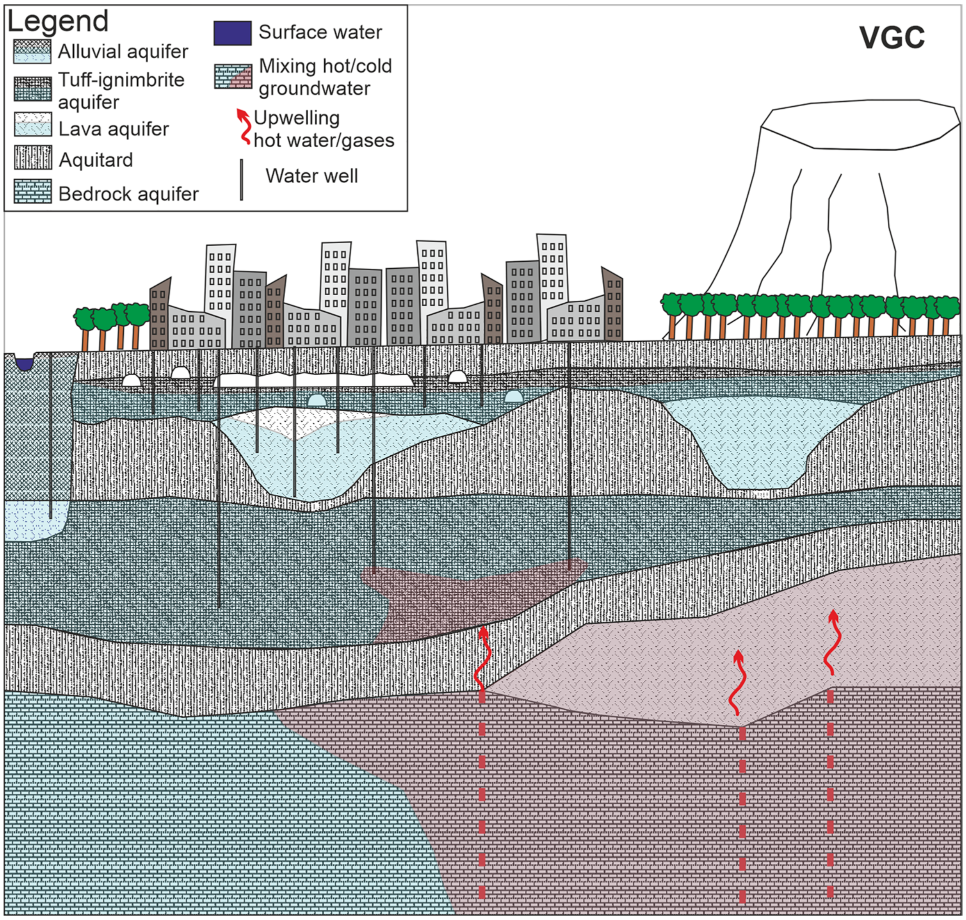

Fig. 3 Volcanic groundwater cities conceptualization - These kinds of cities are characterized by aquifers with a particular setting, usually influenced by the volcanic depositional activity, with frequent abrupt changes in permeability. Moreover, thermalized and mineralized groundwater is frequently found, even if the volcano is quiescent or no longer active; also the presence of natural background contaminants is possible in these contexts due to the volcanic nature of rocks. Where cities have a long history there is the possibility that shallow volcanic rocks (especially tuff deposits) were mined for quarrying building materials and thus there are underground caves which can increase the surface instability, and there is the possibility that these caves are used for illegal waste disposal, with negative consequences for groundwater as well

to process, transfer, and use geothermal heat (EEA 2010). Where cities have a long history there is the possibility that shallow volcanic rocks (especially tuff deposits) were mined for quarrying building materials and thus there are underground caves which can increase the surface instability, and the possibility for these caves to be used for illegal waste disposal, with negative consequences for groundwater as well.

Hard-rock and karst groundwater cities (HRGC - KGC)

Hard-rock cities are those cities that grew up on massive rocks and thus are mainly characterized by fissured aquifers or, in the case of carbonate rocks, also by karst aquifers (Fig. 4). For example, Porto (Portugal) developed on granites and a gneiss-mica schist complex, and the local groundwater flow paths are mainly governed by secondary permeability features such as faults, fractures, and fissures locally enhanced by weathering to produce discontinuous productive zones (Afonso et al. 2007b, 2020). In Colombo (Sri Lanka), over 90% of the entire non-coastal area lies on the metamorphic hard-rock formation (quartzite and marble); there exists a weathered water-bearing rock formation over the hard rock that accommodates a fair amount of groundwater resources (Herath and Ratnayake 2007). In the Eastern Precambrian province of Brazil, the urban area of Sao Paulo is the most heavily populated and industrialized area of the country, and most groundwater is obtained from discontinuous bodies of sand of Tertiary age and fractures and joints in the Precambrian rocks (Schneider 1963). Hard-rock groundwater cities with a karst bedrock can be defined as karst groundwater cities (KGC), such as the Orlando area (Florida, USA), where at least 11 new sinkholes (mean diameter is 9 m and the mean depth is 5 m) open up each year, and their development has been considered connected to groundwater level variations. The Orlando area is described by Wilson and Beck (1992) as located “on a thickly mantled karst area, and sinkholes form by cover collapse or, less commonly, cover subsidence. Many new sinkholes occur here during April and May, when groundwater levels are usually at seasonal low stands; when the potentiometric surface declines below its mode, more sinkholes than expected per unit time occur”.

Alluvial groundwater cities (AGC)

Alluvial groundwater cities (Foster et al. 2010) can be considered those which are developed in alluvial or generally

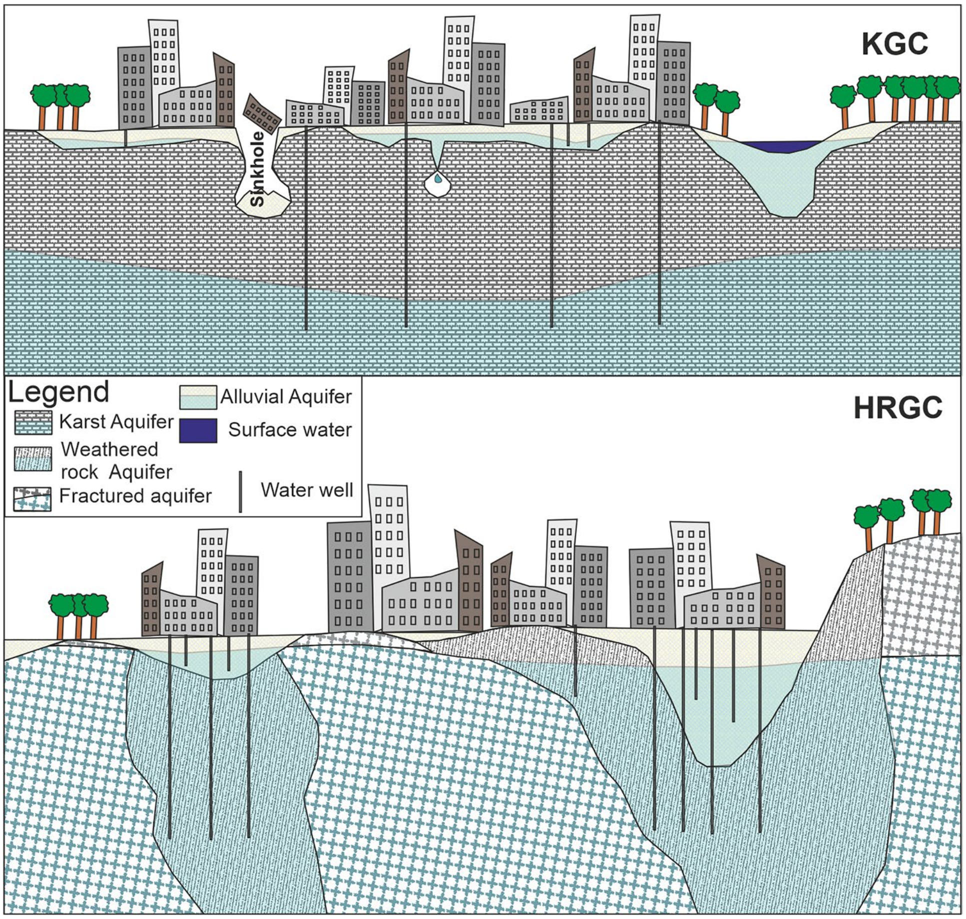

Fig. 4 Hard-rock and karst groundwater cities conceptualization - These kinds of cities are characterized by the presence of massive rocks and thus they are mainly characterized by fissured aquifers or, in the case of carbonate rocks, also by karst aquifers. Groundwater circulation is also possible in more degraded sectors of rock mass. In karst contexts, the groundwater also has an important role in triggering sinkhole formation

sedimentary depositional basins (Fig. 5) or in basins characterized by glacial deposits, where their thickness allows for groundwater circulation that can be useful or can cause interference with the city. Due to the flat morphology that characterizes this kind of geological context and the frequent presence of watercourses, many cities worldwide are in this category. In alluvial contexts, the frequent multilayer setting of the geological units influences the aquifer system geometry; here the quality of abstracted groundwater is typically good when exploiting the deeper aquifers, while the shallower ones are more vulnerable and thus subject to pollution and anthropic pressure. Between the many cities which are in such a context it is possible to cite as examples Berlin and Munich (Germany) (Menberg et al. 2013), Milan (Italy), Lucknow (India), Paris (France), Beijing (China), Ho Chi Minh City (Vietnam) (IGES 2007), and Mexico City (Mexico).

When alluvial groundwater cities arise in piedmont zones, the groundwater setting is usually influenced by the aquifers in the mountains. An example of a piedmont alluvial groundwater city is Beni Mellal City (Morocco), which is characterized by a karst limestone bedrock aquifer in the south and an alluvial multilayer aquifer system in the north, and some outcropping travertines above (El Baghdadi et al. 2019). It is also possible in AGC that the deepest aquifers are in artesian condition, as occurs in Kyiv (Ukraine) where good quality groundwater can be easily withdrawn without using pumps (Shestopalov et al. 2000).

The AGC located in former glacial contexts (e.g. Manchester (UK), Arnhardt and Burke 2020) are composed of glaciofluvial sands and gravels occurring as blanket bodies or as channel deposits in alluvial plains and buried bedrock valleys. Tills are also a major component of glacial terrain and can either behave as aquifers or aquitards since they display highly variable hydraulic conductivities (Ravier and Buoncristiani 2018).

Cold climate groundwater cities (CCGC)

Cities located in regions of the northern hemisphere (subarctic or arctic climate - Obu et al. 2019) have sometimes to deal with permafrost and its related issues (Fig. 6). The permafrost, a type of ground which remains at a temperature below 0°C for at least two consecutive years, affects all hydrologic, geomorphic, and biologic processes in some arctic places, as for example the Siberian plain, reaches several tens or hundreds of meters in depth and it usually constitutes a real barrier to natural aquifer recharge. Furthermore,

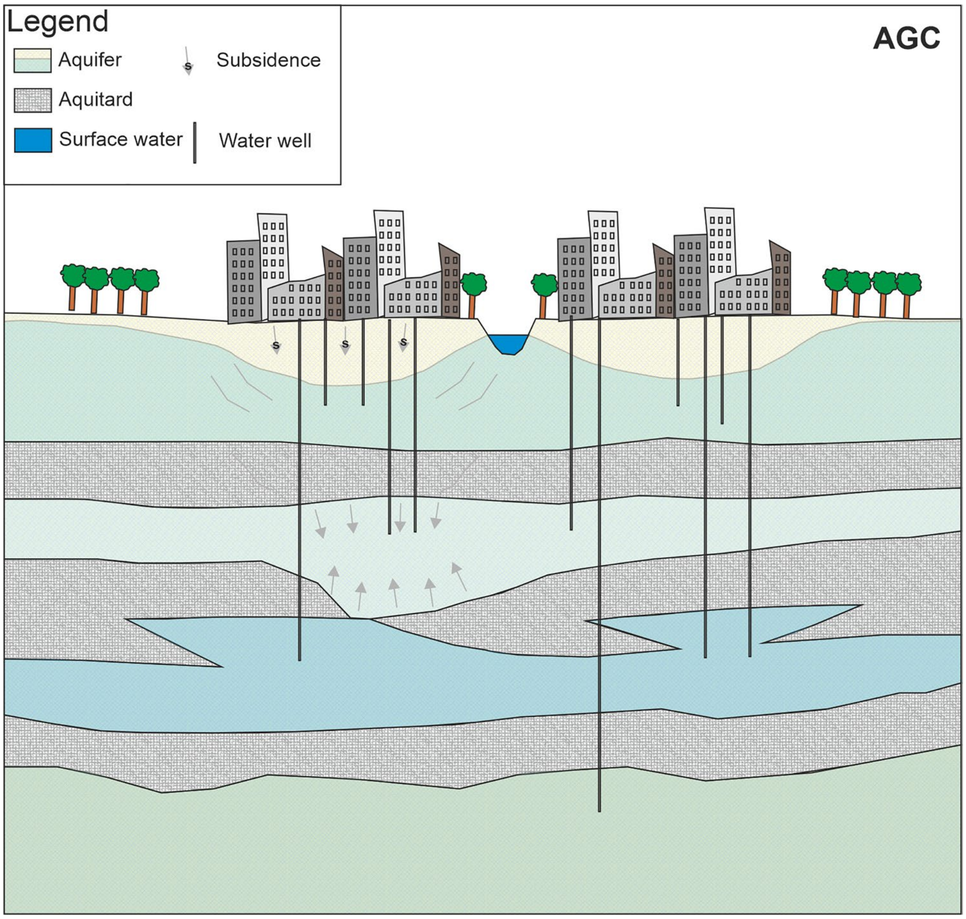

Fig. 5 Alluvial groundwater cities conceptualization- These kinds of cities developed on alluvial or generally sedimentary depositional basins (Fig. 5) or in basins characterized by glacial deposits, where their thickness allows groundwater circulation that is useful or interferes with the city. The frequent multilayer setting of the geological units influences the aquifers' geometry. Subsidence is a typical issue of AGC, especially when aquifers are overexploited

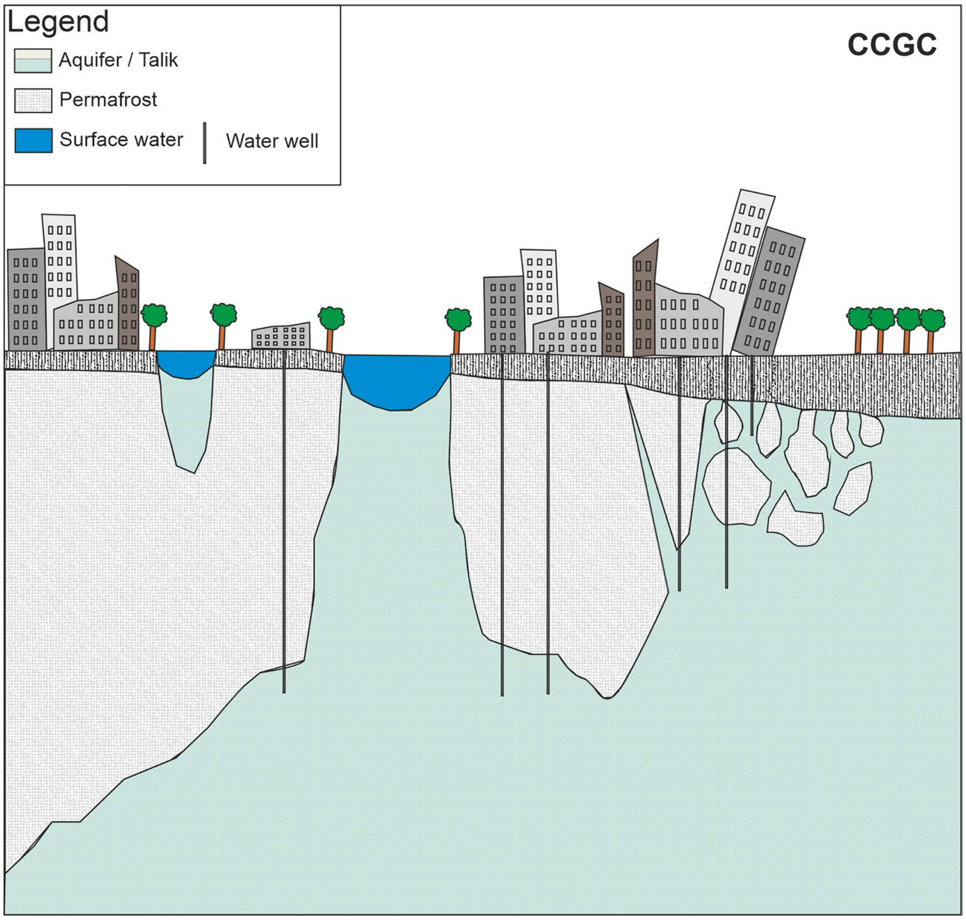

Fig. 6 Cold climate groundwater cities conceptualization - These kinds of cities sometimes have to deal with permafrost and its related issues. Permafrost usually constitutes a real barrier to natural aquifer recharge; moreover, the urban infrastructure and buildings themselves (together with climate change) induce a heat island effect that contributes to the ground thawing generating ground instability

cities built on permafrost can trigger several issues related to shallow groundwater in this environment. First, the urban infrastructure and buildings themselves induce a heat island effect that contributes to the ground thawing. Changes in the ground thermal regime can, in fact, greatly reduce the permafrost's capacity to carry structural loads imposed by buildings and structures, as experienced (e.g.) in Norilsk (Russia) (Shiklomanov et al. 2017), where about 60% of buildings have been damaged by permafrost thaw, or in the Mohe County (China), where urbanization has a significant influence on permafrost degradation (Yu et al. 2014). Moreover, the losses from city water and wastewater infrastructures, which are warmer than the permafrost, contribute to the ground thawing and generate local shallow groundwater circulation systems. Coupled with the general global warming trend, the melting effects on permafrost and cities built above it are considerable.

Notwithstanding the general low recharge capacity and the difficulties in reaching productive aquifers, the presence of taliks (areas of unfrozen ground surrounded by permafrost) allows considerable recharge and connection between unfrozen aquifers (Pavlova et al. 2020). In such conditions, there is thus the possibility to reach groundwater for local community supply, even if dealing with technical difficulties sometimes, especially during the past, as reported (e.g.) by Chu (2017) for the city of Yakutsk (Russia). Although rarer, some cities, villages, and anthropic infrastructure in mountain environments can deal with permafrost issues, like those located in the Qinghai-Tibet Plateau (China) (Cheng and Jin 2013).

Arid climate groundwater cities (ACGC)

As stressed by Sharp et al. (2003) “in general, aquifers run little chance of being exhausted. However, exceptions may occur in arid or semi-arid regions” (Fig. 7) where, due to the very scarce rainfalls, perennial rivers and lakes usually do not exist, and surface water resources are scarce to absent, except for the mountainous areas. Some arid zones have very shallow groundwater systems which are more sensitive to the few seasonal recharge events, or very deep “fossil” groundwater resources, which are sometimes very large but not renewable (Foster and Loucks 2006), such as the case of the Mega Aquifer System (MAS) in the Arabian Peninsula (Sultan et al. 2019). From the climate change perspective, such cities could be the first to experience problems with water supply soon.

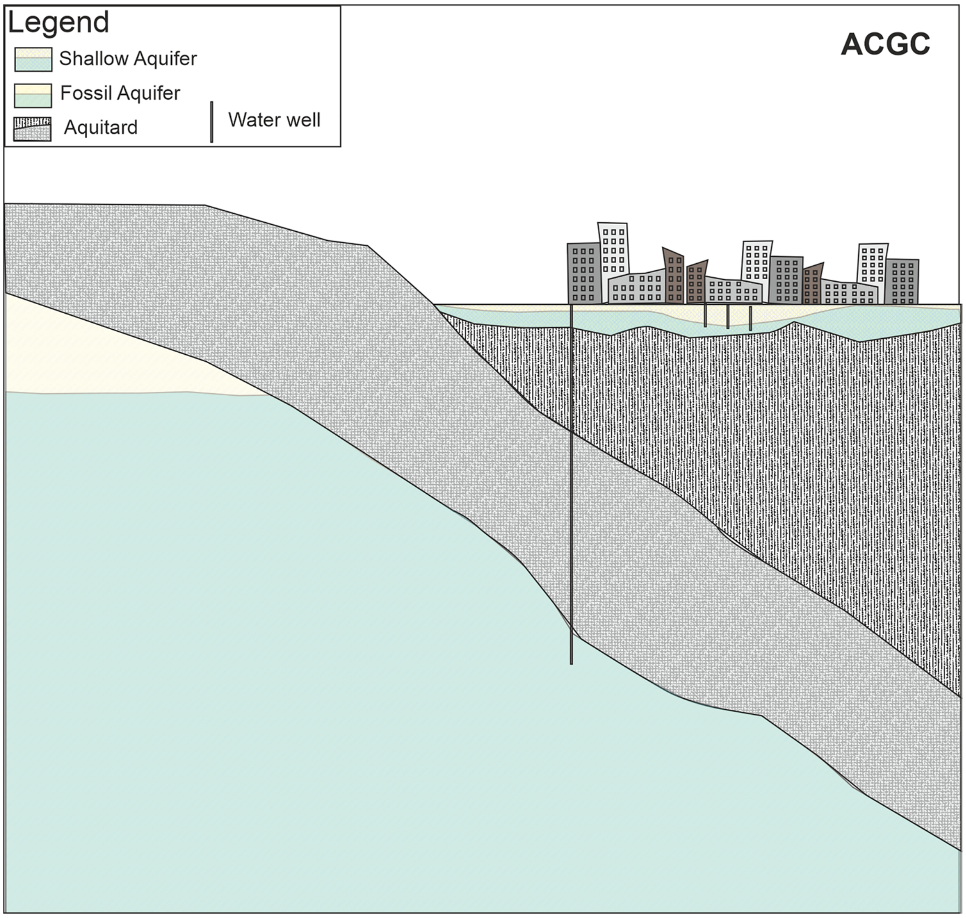

Fig. 7 Arid climate groundwater cities conceptualization - These kinds of cities have sometimes very shallow groundwater systems which are more sensitive to the few seasonal recharge events, or sometimes very deep "fossil" groundwater resources, which are sometimes huge but not renewable

One peculiar issue associated with arid-climate cities is reported by Shanahan (2009): "over time, low-hydraulic-conductivity hardpans develop in desert soils from the residuals left by evaporation; when a city arises over these hardpans, the water added by leakage from water and sewer lines and irrigation of parks and gardens can stagnate on the hardpan layer and cause surface flooding and water intrusion into buildings". Kuwait City (Kuwait), for example, due to this phenomenon, has seen water tables rise as much as 5 m (Al-Rashed and Sherif 2001).

To cite some other ACGC, Tucson (Arizona, USA) uses groundwater from the Avra Valley, which receives minimal recharge so that this aquifer is essentially being mined. Although permanent depletion is not generally a threat, it is easy for a growing city's demands to exceed an aquifer's safe yield. Of concern are situations in which water levels drop so far that pumping becomes very expensive or water yields are severely diminished (Sharp Jr et al. 2003). For example, in Waco and Dallas (Texas, USA), artesian aquifers formerly fed wells that were free-flowing, but water levels have fallen many tens of meters and the artesian condition has been lost (Sharp Jr 1997).

General urban groundwater-related issues

Several issues relating to the interaction between groundwater dynamics, properties, and the city fabric can be identified. Some of the issues listed below are general issues that are possible in any kind of groundwater-city, some are instead typical of specific city typology.

Changes to the water cycle and rise of the water table

According to Lerner (1997), the classical view that cities reduce recharge because of the high proportion of impermeable surfaces has been recognized as incorrect. Although hydrologists have shown that urbanization increases storm runoff (Scalenghe and Marsan 2009), there is no direct evidence that the increased runoff is at the expense of recharge, and it may well be at the expense of evapotranspiration, given the reduced plant cover in cities. In addition, water losses from water mains and sewer systems lead to additional groundwater recharge (e.g., Minnig et al. 2018). Hydrometeorologists have shown that cities have microclimates with increased dust in the air and higher temperatures, affecting precipitation and evapotranspiration rates. More critical for recharge is how the hydrological pathways are altered due to rainfall interception by relatively impervious surfaces such as roofs, roads, and other sealing infrastructure.

The widely recognized changes to the groundwater cycle in urbanized areas, are synthesized by Howard et al. (2015) as follows:

- *“Substantial increases in recharge,* because the reduction consequent upon land impermeabilization is more than compensated by water mains leakage, wastewater seepage, stormwater soak ways, and excess garden irrigation.
- *Large subsurface contaminant load* from in-situ sanitation, sewer leakage, inadequate storage and handling of community and industrial chemicals, and disposal of liquid effluents and solid wastes.
- *Significant discharge* because of inflow to deep collector sewers and infrastructure drains.”

These urban modifications are in continuous evolution, resulting in changes to the groundwater regime, which can seriously reduce the resilience of urban infrastructure (Howard et al. 2015).

The application of strict rules (mainly for environmental reasons) on groundwater extraction in urban areas, and the evolution of local groundwater demand over time, can lead to a significant rise in groundwater table which can be a significant hazard for urban structures (Marinos and Kavvadas 1997). Johnson (1994) listed several adverse effects of groundwater-level rise on both subsurface structures and on the environment, which have been reported together with other examples in Table 1.

To propose some examples, in London (UK), rising groundwater is now flowing in subsurface structures built during the time of a lower groundwater level; as reported by Shanahan (2009), “the water levels measured in an observation well at Trafalgar Square in the downtown area reached its lowest levels in the 1950s and early 1960s, but have since recovered nearly 50 m due to reduced groundwater pumping”. In Rome (Italy), groundwater flooding effects are more evident in the reclamation areas close to the city's coastal sector, where a flooding component due to groundwater rise has been recently recognized (Mancini et al. 2020). Finally, in Buenos Aires (Argentina), the "rebound" of the water table has caused malfunction of in-situ sanitation systems, overloading, and overflowing of sewers, flooding of basements, rising dampness in domestic dwellings, and disruption to parts of the urban infrastructure (Foster et al. 2010).

Artificial recharge from water and wastewater network losses

According to Foster et al. (1994), “the urbanization effect on recharge rate arises both from modifications to the natural infiltration system, such as surface sealing and changes in natural drainage, but also from the introduction of the water service network, which is invariably associated with a large volume of water mains leakage and wastewater seepage”. Whatever the source, the water supply is distributed throughout the city to consumers and collected for wastewater disposal. Thus, the water can find various routes to recharge groundwater, such as over-irrigation of parks and gardens, leakage of water mains, and septic tanks. The infiltration of wastewater has significant quantitative resource benefits, storing the water in the aquifer for future use, but it also represents a potential health hazard because it can pollute the groundwater used for potable water supply (Foster and Chilton 2004). Thus, the recharge from the water supply system could range from 90% of the supply in unsewered cities to 10% in cities with exceptionally well-maintained mains and sewers (Lerner 1997).

In hydrological terms, excess rainfall increases the volume of water circulating in distribution systems, also in moderately humid areas. (Foster 1990). However, it is not easy to evaluate this recharge contribution due to the complexity of the city setting, the different ages of the distribution network components, and the possibility that lost water can be intercepted by sewers or tree roots. By way of cases studies, some authors have evaluated this recharge rate, such as for the cities of Lima (Perù) with a rate of 1400-1600 mm/a (Foster and Chilton 2004; Geake et al. 1986), Tokyo (Japan) with a rate of 440 mm/a (ARAI 1990), Birmingham (UK) with a rate of 180 mm/a (Lerner 1988), and Merida (Mexico) with a rate of about 600 mm/a (Foster et al. 1994). While not all methods used to evaluate recharge in natural systems can be extended to urban systems, the use of natural or artificial tracers and environmental isotopes have been successfully proposed by Vazquez-Sune et al. (2000); Vázquez-Suñé et al. (2010) for the city of Barcelona (Spain). The tracers used in this recharge quantification were Cl^-, SO_4^{2-}, F^-, N_{total}, ^{18}O, ^{3}H, ^{34}S, D, Br, EDTA (ethylenediaminetetraacetic acid), Zn, Ra and B.

Interaction between buried structures and groundwater

Urban buried structures disturb the natural flow and quality of groundwater. In their review, Attard et al. (2016b) described lots of studies that deal with the individual impacts of underground structures on groundwater flow. They reported several approaches that developed sensitivity

Table 1 Adverse effects of rising water table in the urban environment, modified after Johnson (1994)

Effect	Target
Reduction of the bearing capacity of shallow foundations	Structure
Increase in water pressure under foundations and floor slabs, causing uplift	Structure
Expansion of heavily compacted fills under the foundations	Structure
Leakage of groundwater (or moisture) into basements of buildings and service ducts	Structure
Increase of load on retaining systems and basement walls of buildings	Structure
Corrosion effects	Structure
Ground heave due to reduction of effective stresses caused by increasing pore water pressure	Ground
Settlement of poorly compacted fills upon wetting	Ground
Ground collapse in case of soils with high collapse potential with rising water table	Ground
Increase of drainage need and potential instability of temporary excavations	Ground
Propagation of mobility of contaminants contained in the previously partially saturated zone	Environment
Adverse effect on root systems of urban vegetation	Environment
Flooding of underground infrastructure	Infrastructure
Decrease of efficiency of artificial drainage systems	Infrastructure
Effect on electricity hubs	Infrastructure

analysis or analytical solutions to quantify the barrier effect of impervious structures and the interaction (i.e., infiltration or exfiltration rate) between sewer and water supply networks. This is a typical situation where modeling approaches are able to show the spatial and temporal extent of groundwater disturbances generated by underground structures in the urban areas (Attard et al. 2016a). One crucial issue in the city groundwater planning is the cascading effect of the possible modification of urban groundwater flow on groundwater quality and quantity.

Groundwater quality issues

Excluding the saltwater intrusion which is typical of CGC and LDGC, decreasing water quality and pollution of rivers and groundwater resources is one of the main threats to water sustainability in developed urban areas (Engel et al. 2011). However, it must be acknowledged that preventing pollution of shallow aquifers in urban areas is essentially difficult (Morris et al. 1997). In fact, as Burri et al. (2019) highlighted, “urban sprawl, globalized pharmaceutical production and consumption, insufficient wastewater infrastructure, shortage empirical data on water quality, and in some cases, the insufficient emphasis on groundwater as a renewable resource are indeed all hampering the complex process of managing groundwater quality”. Furthermore, groundwater quality problems typically evolve over long periods, and complication arises where groundwater is exploited by many private (sometimes illegal) boreholes, inadequately sited and poorly constructed with an inadequate sanitary seal. These practices can provide pathways for rapid downward migration of contaminants to deeper high-quality aquifers and conduits for cross-contamination (Eberts et al. 2013; Morris et al. 1997). The groundwater pollution due to urbanization processes is generally related to the diffusion of nitrogen compounds, a rising salinity level, and an elevated concentration of dissolved organic carbon. Moreover, many cases of petroleum compounds and chlorinated hydrocarbons are usually present as soil and groundwater contaminants, and sometimes also viruses and bacteria can be found. This is especially possible in urban residential districts without or with incomplete mains sewerage systems, where seepage from unsewered sanitation systems, as (e.g.) for the City of Lusaka (Zambia) (Adelana et al. 2008), probably represents the most widespread and severe diffuse pollution source (Foster et al. 1999).

In an urban setting, preferential pathways along pipelines, conduits, and old wells can also affect contaminant transfer and cross-contamination in groundwater. Underground gasoline storage tanks frequently leak, discharging gasoline into the subsurface. As it travels in sewer trenches, the pollutant can take a zigzagging course from one street to the next (Shanahan 2009). Moreover, as always Shanahan (2009) highlighted, “the disparate fill material used in many cities can create preferential pathways for groundwater flow and contaminant migration, as well as old wells can create preferential pathways for vertical flow, sometimes spreading contaminants from a contaminated shallow aquifer to deep uncontaminated aquifers; thus, subsurface infrastructure can have a significant but local effect on groundwater flow and contaminant transport and must be considered”. If NAPL (non-aqueous phase liquid) petroleum contaminants are frequently present in large cities' shallow groundwater due to the many gasoline station tanks' possible spills, much DNAPL (dense non-aqueous phase liquid) products such as chlorinated solvents were found also in many deeper city aquifers in the last decades. These contaminations usually derive from some industrial activities, sometimes no longer existing in the cities, but due to their long persistence in the aquifers are today again identifiable even in cities with no high industrial vocation, such as (e.g.) Rome (Italy) (Bonfà et al. 2017; La Vigna et al. 2019).

Moreover, according to Eberts et al. (2013), "human activities can cause local- and regional-scale changes in aquifer geochemical conditions and indirectly increase (or decrease) concentrations of natural contaminants in groundwater and water from public-supply wells: for example, groundwater near a landfill can have elevated concentrations of arsenic, yet the source of the arsenic is not the landfill's contents; instead, the source is a geologic part of the solid aquifer material." The combination of microorganisms' activity in organic carbon degradation and derived anoxic conditions allows the release of Arsenic downgradient from the landfill.

In recent years, drugs of abuse (DAs) and their metabolites have been recognized as environmental contaminants. These compounds, which have been detected in the sewer systems and thus in groundwater of many cities (e.g. Barcelona, Spain) (Jurado et al. 2012) have become a significant cause for concern because of their occurrence and toxicity, and persistence are not well known.

Drought

Drought is a concern in many cities, and this issue is more evident also due to the increasing global warming, especially for those located in arid and semi-arid zones (ACGC), where it is expected that groundwater recharge will decrease consistently by 30 to 70% or even more (Van der Gun 2012). Accra (Ghana) and its hinterland exemplify an African city with chronic water shortages, where groundwater resources offer opportunities to improve resilience against recurring droughts and where water supply diversification is crucial (Grönwall and Oduro-Kwarteng 2018). In Mexico City (Mexico) (e.g.), over the decades, the rising, unsustainable (in the long term) demand for water has put enormous pressure on local and neighboring surface water and groundwater supply sources and has caused both economic and environmental damage. The now fully developed practice of importing water to meet urban demand, coupled with water scarcity, has led to a series of social and political conflicts over the distribution and management of water resources in the city (Mahlknecht et al. 2015)

Subsidence

When aquifers are overexploited, pore pressure falls, and the ensuing aquifer compression can cause land subsidence or sinking of the earth surface (Engel et al. 2011). Subsidence issues related to groundwater extraction are present both in coastal and delta cities (CGC - LDGC) as previously cited, and interior parts of AGC such as Lhasa (China) (Ji-hui et al. 2005), Mexico City (Mexico), or Las Vegas (USA), where differential subsidence disrupts roads and infrastructure. In these contexts, subsidence may create flooding problems where it changes the slope of natural drainage pathways (Sharp Jr 1997). In New Orleans (USA), subsidence induced by groundwater withdrawals played a crucial role in the impacts associated with Hurricane Katrina (Jones et al. 2016). Shanahan (2009) reported as "in London (UK), the layer of London Clay has shrunk as it has become dewatered", determining a lowering of the land surface in Central London by 20 to 25 cm since 1865 with a localized maximum settlement of about 50 cm (Downing 1994). As reported by Venvik et al. (2020), "for the Bryggen Wharf, in central Bergen (Norway), there is a strong link between water and subsidence due to reduction in the water content in the subsurface cultural-heritage layers and lowering of the groundwater levels, leading to the decay of organic layers as well as historical wooden foundations and thereby subsidence".

Moreover, coastal cities subject to subsidence are typically more vulnerable to the climate-change effects on sea level. Rising sea level might aggravate saltwater intrusion and there could be impacts associated with extreme weather events, such as storms and floods (Maliva 2021). This is particularly evident in Jakarta (Indonesia), defined by Lyons (2015) as one of the "fastest-sinking cities", where the combined effects of land subsidence, also enhanced by groundwater overexploitation, and sea level rise, introduced other cascading effects such as the tidal flooding phenomena (Abidin et al. 2010).

Groundwater heat island effect

The temperature regime is more complex in the urban subsurface environment than in rural, less disturbed environments. According to Epting and Huggenberger (2012), "thermal groundwater regimes in urban areas are affected by several anthropogenic changes, such as surface sealing or subsurface constructions and groundwater use. Moreover, the extension of subsurface structures and the diffuse heat input of heated buildings have resulted in elevated groundwater temperatures being observed in many urban areas", such as (e.g.) in Tokyo (Japan) (Taniguchi et al. 1999), in Winnipeg (Canada) (Ferguson and Woodbury 2004), in Cologne and Munich (Germany) (Menberg et al. 2013;

Zhu et al. 2010), in Istanbul (Turkey) (Yalcin and Yetemen 2009), in Jakarta (Indonesia) (Lubis et al. 2013), and in Basel (Switzerland) (Epting and Huggenberger 2012). Understanding groundwater heat transport is essential for the design, performance analysis, and impact assessment of thermal devices (Epting and Huggenberger 2012), but also for the environment. According to Zhu et al. (2010) "factors that cause the urban heat island effect in the subsurface are similar to those that increase surface air temperature, such as indirect solar heating by the massive and complex urban structures, anthropogenic heat losses, and land-use change; moreover, the anthropogenic thermal impacts are more persistent in the subsurface because of the slow conduction properties of the subsoil; this extra heat stored in urban aquifers is sometimes considered underground thermal pollution". That is because thermal anomalies can sometimes change the groundwater chemical balance and the groundwater-rock interaction and facilitate pollutants dissolution, mineral weathering, chemical adsorption, and desorption, gas solubility, and microbial redox processes (Saito et al. 2016), but also can change very precarious balances in urban groundwater-dependent ecosystems.

Sustainable and virtuous uses of urban groundwater and its related value

There are some general best practices which are already presented in the *Introduction*, which are valid in all city types and contexts, and are as follows: developing a city-scale groundwater monitoring network; having a city-scale hydrogeological map and or a 3D groundwater model; and, increasing citizens' and administrators' awareness of matters related to groundwater, making it visible.

Intending to understand the resilience value for cities in taking advantage of sustainable and virtuous groundwater uses, some specific best practices and examples of groundwater-related resources are presented as follows.

Marginal groundwater exploitation

"Poor groundwater" is that resource that cannot be utilized for traditional supply exploitation, as it is the water of contaminated (both by human activities and by natural contaminants) aquifers or that of saline aquifers. In some cities, incentives for exploiting this lower-quality groundwater for non-potable private or industrial uses are required (Morris et al. 1997). In Eindhoven (The Netherlands) (e.g.) Sommer et al. (2013) argued that "combining aquifer thermal energy storage (ATES) and groundwater remediation can be beneficial for both. From the ATES point of view, it opens opportunities for application in contaminated areas. From a remediation point of view, it could help to accelerate groundwater quality improvement." The most common use of these poor groundwaters is related to industrial processes and mainly with saline water.

Instead, a "poor aquifer" can be defined as an aquifer from which the groundwater exploitation is no longer convenient, attractive, or possible for multiple reasons. It is the case (e.g.) of the proposal made by Gambolati and Teatini (2013) for the historic city of Venice (Italy), which is subject to periodic flooding, also due to subsidence, which with climate change and rising sea levels will become increasingly frequent and of ever greater magnitude. The proposal consisted of injecting seawater into the deep saline confined aquifers at a depth of about 650-1000 m to increase the deep pressure and thus obtain a slow and homogeneous ground rising of about 25-30 cm in approximately ten years.

Aquifer storage and recovery (ASR) and managed aquifer recharge (MAR)

Even if the groundwater is not used for water supply, urban aquifers are a potential storage location for stormwater, reducing surface runoff from impervious areas (Göbel et al. 2004). Managed aquifer recharge (MAR) and aquifer storage and recovery (ASR) are processes enhanced by humans that convey water underground to replenish aquifers. Although the terms MAR and ASR are often used interchangeably, they are separate processes with distinct objectives (EPA 2021). MAR is used to replenish water in aquifers with an intentional action but taking advantage of the natural geological predisposition to infiltrate water. ASR is a technique where water is artificially injected into aquifers during periods of excess water availability and withdrawn from aquifer storage when needed (Sharp Jr 1997). These techniques are widely and successfully applied in Australian cities like Adelaide (Dillon et al. 2002) and Melburne (Dillon et al. 2010; Mudd et al. 2004). According to USGS (2018), "spreading basins are the primary technique used for artificial recharge; ideally, basins are located adjacent to natural streams, have sand or gravel beds, and good hydrologic connection to a well-defined, high-storage-capacity aquifer. Aquifer injection wells are instead designed to place recharge water directly into an aquifer; the same wells may be used for recovery. In general, water quality requirements are highest for aquifer injection."

In many countries, these presented methods are still considered new technologies. Overall, the policies and legal framework applicable to aquifer recharge are scarce and at an early stage, especially in developing countries (Escalante et al. 2020).

Sustainable drainage systems (SuDS) and green infrastructure

With due differences between cities, paved surfaces are some of the most common components found in the urban environment. These surfaces normally increase the surface runoff and significantly decrease infiltration and evapotranspiration (Burri et al. 2019). De-sealing means restoring the natural soil infiltration capacity (Naumann et al. 2019). The objective can be reached using several techniques used in those commonly named green infrastructure systems whose effect is to allow regular or additional recharge.

Green infrastructure refers to green spaces linked together continuously, and they have more recently emerged as a set of stormwater management instruments that complement gray infrastructure; in fact, they mitigate the stormwater effects on the urban surface by taking advantage of soil and vegetation properties to enhance water infiltration (Berland et al. 2017). Examples of green infrastructure include rain gardens or bio-retention areas, permeable pavements, bioswales, green roofs, stormwater curb cutouts (Berland et al. 2017). As reported by Armson et al. (2013), "incorporating trees into urban landscapes can substantially reduce stormwater runoff by improving infiltration; in Manchester (UK), tree pits containing small trees reduced runoff from asphalt control plots by 62%". Moreover, Hollis and Ovenden (1988), argued that "there was a marked reduction in salinity and increase in dissolved oxygen concentrations in the upper part of the aquifer downgradient of the infiltration basins; concentrations of toxic metals, nutrients, pesticides, and phenolic compounds in groundwater near the infiltration basins were lower than upgradient."

Groundwater-dependent ecosystems protection

According to Bricker et al. (2017)," the multiple functions that ecosystem services provide concerning the ground beneath urban areas are increasingly recognized by city practitioners. For example, groundwater provides multiple services, primarily for potable water supply and by diluting and attenuating contaminants and acting as a medium for exploiting ground heat". Nevertheless, from an environmental and ecosystem sustainability perspective, the groundwater resource is almost completely overlooked. Groundwater's critical ecological functions are almost universally unrecognized and unheeded, although groundwater provides base flows to springs, streams, lakes, wetlands, and areas of phreatophytes, and the average contribution of groundwater to surface water supplies amounts to approximately 50% (Guo et al. 2011).

Urban groundwater-dependent ecosystems can be the natural river banks themselves and any surface water body directly connected with groundwater dynamics. From an urban resilience perspective, groundwater-dependent ecosystems in a city decrease the heat island effects and decrease the pressure of heavy rainfall and river floods due to the natural soil presence and the above-vegetated surface.

Low-enthalpy geothermal energy

Subsurface temperatures are often higher below cities and thus, urban groundwater is a valuable energy reservoir (Schirmer et al. 2013). Heat pump installations could exploit this significant geothermal potential (Allen et al. 2003; Zhu et al. 2010) but in contexts where many closed and open-loop geothermal energy systems coexist, thermal interference is possible between adjacent systems. Moreover, the thermal interference in an urban context may occur also due to the proximity to buried services and structures, sewerage, and water withdrawal. According to Patton et al. (2020), "a paucity of baseline temperature data from urban aquifers could also determine poor system design and performance, in this perspective urban groundwater monitoring networks are required to increase confidence for investors while supporting evidence-based regulatory targets". Groundwater temperature city maps, as performed (e.g.) in Cardiff (UK) (Farr et al. 2017) and Rome (Italy) (La Vigna et al. 2015a), are handy tools for city planners who want to manage groundwater low-enthalpy thermal uses efficiently.

Discussion

Are urban groundwater management and knowledge playing a role in city resilience? To answer this question, it is necessary to recall the city resilience aspects and keywords proposed in the *Introduction*. It is thus necessary to understand if the groundwater services provided to a city area are essential and what happens to the city in case of shocks and/or stresses related to such services, and on the other hand, to evaluate the recovery capacity and preparedness of a city system to mitigate any one of these possible issues. The presented city groundwater types and the possible issues and best measures to put into practice are summarized and compared in Table. 2. The table presents both general groundwater-related issues which are possible in every city, and issues more specific for the single city category. Moreover, both the general best practices valid for every city and some more specific practices are listed.

The presented issues can affect different city functions. In the work of Morris et al. (1997) several analyses were developed to list the benefits and costs in urban use of the subsurface environment and urban groundwater problems and management requirements. With a similar approach, in Table 3, some possible cascading effects due to the groundwater services' interruption in a city are proposed.

Table 2 Comaprison between city typology, issues, and best practices

City type[a]	Possible general issues Valid for all city types	Possible typical issues	General best practices Valid for all city types	Specific best practices
CGC	Groundwater quality issues; Changes to water cycle and water table rise; Interaction between buried structures and groundwater; Artificial recharge from water and wastewater network losses; Groundwater heat island effects	Groundwater quality issues (saltwater intrusion)	Groundwater monitoring network development; City-scale hydrogeological map; Citizens' and administrators' groundwater awareness; Sustainable drainage systems and Blue and green infrastructure; Marginal groundwater exploitation; Groundwater-dependent ecosystems protection	-
LDGC		Subsidence and related sea rising effects; Groundwater quality issues (saltwater intrusion).		-
AGC		Subsidence		-
HRGC		-		-
KGC		Sinkhole collapse due to groundwater level variations		-
VGC		Upwelling deep gases and change in the acidity of waters		Low-enthalpy geothermal energy
CCGC		Groundwater heat island effect and permafrost melting		-
ACGC		Drought		Aquifer storage and recovery (ASR) and managed aquifer recharge (MAR); Marginal groundwater exploitation.

[a] Groundwater city (GS) types: *CGS*, coastal, *LDGC*, lagoon and delta; *AGC*, alluvial; *HRGC*, hard-rock; *KGC*, karst; *VGC*, volcanic; *CCGC*, cold climate; *ACGC*, arid climate

Table 3 Cascading effects due to the interruption of groundwater services in a city

VALUE (Direct role)	SHOCK (What happens in case of stop or crisis)	CASCADING EFFECTS (And thus…)
1) Drinking water supply	Health and social problems	Lack of hygiene, dehydration, epidemics, popular unrest
2) Green areas' irrigation water supply	Soil, grass and plants go to be dry and death	More heat wave effects, more fire hazard, less permeability, and less water retention effects
3) Agriculture and industry water supply	Production stop	Economic losses, loss of jobs, loss of well-being, popular unrest
4) Urban surface infiltration	High runoff	Crisis of drainage network, urban floods, local blackouts, traffic jams, landslides
5) Discharge drainage in reclamation areas	Water table rising	Groundwater flooding, urban flood, local blackouts, traffic jams
6) Urban groundwater-dependent ecosystems survival	Ecosystem damage	Loss of environmental value

Analysis of Table 3 shows how the conjunctive use of different sources provides more redundancy and thus higher resilience for a city. Highly centralized, single-source systems may lack the flexibility to meet unexpected events, such as natural disasters. Surface waters (e.g.) can become contaminated with unexpected pollutants (due to flooding, industrial accident, nasty spills, or sabotage). If such contamination occurs, if treatment plants malfunction or reservoir levels drop below intake levels, the urban water system depending solely upon a few large surface reservoirs or a few large intakes, becomes essentially inoperable (Sharp Jr 1997). For example, it is possible to cite the recent Cape Town (South Africa) water supply crisis of 2017-2018, when a drought caused severe resource depletion and consequent domestic supply restriction (Olivier and Xu 2019). This situation, as stated by Foster et al. (2020), "is a classic example of what can arise under climatic stress, where a major municipal water-service utility relies exclusively on a sizeable surface-water reservoir and has not diversified its sources to include local groundwater systems".

It is thus possible to figure out (Table 4) the characteristics of a groundwater-resilient city (GWRC) and try to imagine what happens in an ideal city system that developed all possible virtuous practices related to local groundwater systems. In essence, the table is constructed by putting together the keywords of the urban resilience concepts mentioned in the *Introduction* and the presented hydrological dynamics. The table consolidates the view that, of these keywords, preparedness and groundwater awareness of the cities' citizens and administrators are very effective actions for a groundwater-virtuous city. In this sense, defining an urban groundwater virtual "helpdesk" could be a good practice to increase citizens' awareness. It would require periodical update of groundwater information in an accessible manner. e.g., dynamic websites with updated monitoring information, and annual groundwater reports are a means to meet this goal.

Conclusions

Shanahan (2009) defined groundwater as the ultimate "out of sight, out of mind" resource. It is difficult and expensive to monitor and manage, and there is usually no oversight until some crisis intervenes. According to Coaffee and Lee (2016), "prior system management has not provided resilience: groundwater has boomeranged through different problems at different times, even changing from an essential resource in preindustrial cities to a nuisance in post-industrial cities. Groundwater is a problem in considerable measure because it is "out of sight and out of mind." The public and even decision-makers know little about the state of the groundwater resource." As a result, poor groundwater quality or level changes might persist for years or decades without being addressed or even discovered. As previously presented, many cities monitor groundwater levels regularly; if visualized and publicly shared, such information could remedy the out-of-sight, out-of-mind problem and allow for more resilient management of the resource. Groundwater data may be accessed and visualized easily, allowing city

Table 4 Characteristics of a groundwater-resilient city (GWRC)

SHOCK (Probable shock involving goundwater)	VALUE (What happens)	RESILIENCE DIVIDEND (And thus…)
Drought and heat waves	*Aware* and *prepared* people and managers make a responsible use and distribution of water	Water demand is lower
	Redundant water supply system is activated	Continuity of water distribution is ensured
	Groundwater recharge has been managed and *monitored*	Green-area irrigation water supply is possible, the city is cooler, the soil is alive, the natural groundwater recharge is guaranteed, heat is *mitigated*
		Agriculture and industry water supplies are possible, and the well-being is maintained
Heavy rain	The urban surface has been *adapted* and made more permeable	The runoff is less, the groundwater is recharged, the urban drainage network is less stressed, and urban floods are *mitigated* or more rapidly *recovered*
	Water tables are *monitored* and harvesting tanks or basins have been built	Lowlands and reclamation areas are less impacted by flooding
Pollution	Groundwater *monitoring* allows one to evaluate pollution migration and distribution	It is possible to better understand where remediation is to be performed and where groundwater needs to be treated
		Contaminated-site remediation activities management, and also protection activities are easier for existing groundwater-dependent ecosystems
	Aware people and groundwater users have a better behavior toward groundwater resources protection	Communication between government and citizens about existing pollution phenomena is easier, and cooperation is greater
Energy demand	The groundwater system *knowledge* is good and the aquifers are *monitored*	The groundwater system's low-enthalpy geothermal potential can be distributed for heating and cooling systems, and greenhouse gas emissions are *mitigated*

technicians and management to assess effects and make real-time adjustments and decisions, while more readily available data could be critical in educating the public and ensuring a more secure groundwater supply. Moreover, citizens can be aware of the groundwater resources under the city and thus put into practice protection and sustainable behaviors.

As highlighted by Grönwall and Oduro-Kwarteng (2018) "groundwater can gain a role as a strategic resource where an integrated approach to urban water management and governance acknowledges the importance of all available resources and moves away from the focus on extensive infrastructure and centralized water supply solutions". In this perspective diversifying the sources is a very useful practice for a city to be more resilient, reducing vulnerability and enhancing preparedness.

Several methods have been proposed in the last decades to achieve integrated groundwater management (IGM) (Jakeman et al. 2016). These methods are essentially based on an approach that holistically considers the broader context of surface water links, catchment management, and intersectoral issues with economics, energy, climate, agriculture, and the environment (Jakeman et al. 2016). The IGM for a city area also needs to consider the anthropic presence and thus the relationships with the urban system and the city life. In Australia, the Water Sensitive City (WSC) and the Water Sensitive Urban Design (WSUD) programs started in the 21st century, to bring a range of benefits that, at the same time, protect the degradation of urban water resources and manage and recycle stormwater, so that cities become more sustainable, liveable and resilient. In practice, the WSUD integrates stormwater, groundwater water supply, and wastewater management (Ashley et al. 2013; Brown et al. 2009). One of the most recent approaches of IGM in urban contexts is proposed for some Chinese cities by Nguyen et al. (2019) with the Sponge City concept. It is based on four principal concepts that are:

- Making the city soil more permeable to absorb and store rainwater and supply water and mitigate stormwater runoff
- Managing the water by self-purification systems and ecologically friendly waterfront design (blue infrastructure)
- Developing green infrastructure to restore, purify and reuse stormwater
- Constructing and using permeable roads

Notwithstanding the sound principles of the Sponge City program, the latter could not be so easy to develop in some countries due to the local legislation that imposes treatment of rainwater circulation above road surfaces.

Looking at the review carried out in this paper it is possible to say that the global vision of cities should consider the relationship with surface water and groundwater. However, as stated by Howard et al. (2015) "the strategic importance of urban groundwater is not yet always reflected by sufficient investment in management and protection of the resource base; in this context, groundwater professionals need to raise awareness of the economic value of groundwater and reveal critical issues in the political economy of resource governance".

Rachwal 2014) proposed their vision called 'Cities and the Underworld', which "deals directly with groundwater systems and highlights a future where infrastructure is increasingly built underground in cities, and where the subsurface is more effectively managed to deliver adequate drainage, water storage, heating, and cooling". These are the first strictly related benefits of correct groundwater management, but as presented before, the positive cascading effects on the cities are much more due to the high level of interdependences of city life with groundwater. Moreover, Foster et al. (2020), highlighted that a "better use of water storage will be critical for water-supply security, and groundwater stored in aquifers offers sustainable solutions for climate change adaptation, at the scale of specific cities and their hinterland catchments".

Therefore, the answer to the question asked earlier in the discussion is: yes, groundwater plays a significant role in cities' resilience, and, as stated by Bricker et al. (2017), "there is a growing body of evidence highlighting the importance of groundwater to support urban living and the impact of urbanism on natural groundwater systems". Consequently, it should be considered by city planners as one crucial aspect in every resilience assessment and strategy. There are many benefits obtained from sustainable groundwater use in cities: the economic value derived from productive uses for drinking water, industry, and garden irrigation; the ecological value provided by supporting urban groundwater-dependent ecosystems; the option value of storing groundwater as an insurance against future water shortages (Grönwall and Oduro-Kwarteng 2018), as well as against fire hazard. Through the clustering proposed, cities could more easily be grouped worldwide by typology and thus compared with respect to groundwater issues and opportunities in common. Therefore, city planners could more easily assess the relative groundwater-adaptation strategies and best practices to raise the resilience of cities.

Appendix

Table 5 Cited cities in the paper; the number is related to the citation order in the text and is the same appearing in Fig. 1 and in the factsheet available as electronic supplementary material (ESM)

Citation order and label	City	State	Continent	City Classification	Reference
1	Miami	USA	North America	KGC - CGC	Williams and Kuniansky 2016
2	Beijing	China	Asia	AGC	Chen et al. 2016
3	Seul	South Korea	Asia	HRGC	Shrestha et al. 2016
4	Rome	Italy	Europe	VGC - LDGC	La Vigna et al. 2016
5	Cardiff	United Kingdom	Europe	CGC	Heathcote et al. 2003
6	Bucharest	Romania	Europe	AGC	Boukhemacha et al. 2015
7	Glasgow	United Kingdom	Europe	HRGC	Dochartaigh et al. 2019
8	Amsterdam	The Netherlands	Europe	LDGC – AGC	de Vries 2007
9	Munich	Germany	Europe	AGC	Menberg et al. 2013
10	Moscow	Russia	Asia	KGC	Osipov 2015
11	Porto	Portugal	Europe	HRGC	Afonso et al. 2007a
12	Paris	France	Europe	KGC	Thierry et al. 2009
13	Lyon	France	Europe	AGC	Attard et al. 2016a
14	Milan	Italy	Europe	AGC	Gorla et al. 2016
15	London	United Kingdom	Europe	KGC - AGC	Shanahan 2009
16	Christchurch	New Zealand	Oceania	CGC - AGC	NIWA 2004
17	Lagos	Nigeria	Africa	LDGC - AGC	Adelana et al. 2008
18	Nairobi	Kenya	Africa	VGC - HRGC	Oiro et al. 2020
19	Karachi	Pakistan	Asia	HRGC - CGC	Khan et al. 2020
20	Adelaide	Australia	Oceania	CGC	Gerges 2006
21	Kobe	Japan	Asia	CGC	Shrestha et al. 2016
22	Tokyo	Japan	Asia	CGC	Shrestha et al. 2016
23	Yokohama	Japan	Asia	CGC	Shrestha et al. 2016
24	Huston	USA	North America	LDGC	Braun and Ramage 2020
25	Jakarta	Indonesia	Asia	LDGC	Lubis 2018
26	Shangai	China	Asia	LDGC	Zhang et al. 2019
27	Venice	Italy	Europe	LDGC	Da Lio et al. 2013
28	Kolkata (Calcutta)	India	Asia	LDGC - AGC	McArthur et al. 2018
29	Dakar	Senegal	Africa	CGC	Adelana et al. 2008
30	Cape Town	South Africa	Africa	CGC	Adelana et al. 2008
31	Manila	Philippines	Asia	LDGC	David et al. 2001
32	Chennai	India	Asia	CGC - HRGC	Senthilkumar 2017
33	Buenos Aires	Argentina	South America	CGC	Anton 1993
34	Recife	Brazil	South America	LDGC	Anton 1993
35	Tripoli	Libya	Africa	CGC	Alfarrah and Walraevens 2018
36	Bangkok	Thailand	Asia	LDGC	IGES 2007
37	Addis Ababa	Ethiopia	Africa	VGC	Adelana et al. 2008
38	Naples	Italy	Europe	VGC	Corniello and Ducci 2019
39	Catania	Italy	Europe	VGC	Ferrara and Pappalardo 2008
40	Reykjavik	Iceland	Europe	VGC	Kononov 1979
41	Colombo	Sri Lanka	Asia	HRGC - LDGC	Herath and Ratnayake 2007
42	Sao Paolo	Brazil	South America	HRGC	Anton 1993
43	Orlando	USA	North America	KGC	Wilson and Beck 1992
44	Berlin	Germany	Europe	AGC	Menberg et al. 2013
45	Lucknow	India	Asia	AGC	Singh et al. 2013
46	Ho Chi Minh City	Vietnam	Asia	AGC	IGES 2007
47	Mexico City	Mexico	North America	AGC – VGC - ACGC	Anton 1993
48	Beni Mellal City	Morocco	Africa	KGC	El Baghdadi et al. 2019

Table 5 (continued)

Citation order and label	City	State	Continent	City Classification	Reference
49	Kyiv	Ukraine	Europe	AGC	Shestopalov et al. 2000
50	Norilsk	Russia	Asia	CCGC	Shiklomanov et al. 2017
51	Mohe County	China	Asia	CCGC	Yu et al. 2014
52	Yakutsk	Russia	Asia	CCGC	Pavlova et al. 2020
53	Kuwait City	Kuwait	Asia	ACGC	Al-Rashed and Sherif 2001
54	Tucson	USA	North America	ACGC	Eastoe et al. 2004
55	Waco	USA	North America	ACGC	Yelderman and Joe 2019
56	Dallas	USA	North America	ACGC	Caldwell 1993
57	Lima	Perù	South America	CGC - HRGC	Anton 1993
58	Birmingham	United Kingdom	Europe	HRGC	Bottrell et al. 2008
59	Merida	Mexico	North America	KGC	Anton 1993
60	Barcelona	Spain	Europe	CGC	Filbà et al. 2016
61	Lusaka	Zambia	Africa	KGC	Adelana et al. 2008
62	Accra	Ghana	Africa	CGC - ACGC	Kortatsi et al. 2008
63	Lhasa	China	Asia	AGC - CCGC	Liu et al. 2018
64	Las Vegas	USA	North America	ACGC	Wyman et al. 1993
65	New Orleans	USA	North America	LDGC	Prakken 2009
66	Bergen	Norway	Europe	CGC - HRGC	Seither et al. 2016
67	Winnipeg	Canada	North America	AGC	Keller et al. 2009
68	Cologne	Germany	Europe	AGC	Zhu et al. 2010
69	Istanbul	Turkey	Europe	HRGC	Ozgul 2011
70	Basel	Switzerland	Europe	AGC	Michel et al. 2017
71	Eindhoven	The Netherlands	Europe	AGC	Bonte et al. 2013
72	Melburne	Australia	Oceania	CGC - VGC	Bell et al. 1967
73	Manchester	United Kingdom	Europe	AGC	Arnhardt and Burke 2020

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