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Review: Impact of underground structures on the flow of urban groundwater

Guillaume Attard^{1,2} & Thierry Winiarski¹ & Yvan Rossier³ & Laurent Eisenlohr²

Abstract Property economics favours the vertical development of cities but flow of groundwater can be affected by the use of underground space in them. This review article presents the state of the art regarding the impact of disturbances caused by underground structures (tunnels, basements of buildings, deep foundations, etc.) on the groundwater flow in urban aquifers. The structures built in the underground levels of urban areas are presented and organised in terms of their impact on flow: obstacle to the flow or disturbance of the groundwater budget of the flow system. These two types of disturbance are described in relation to the structure area and the urban area. The work reviewed shows, on one hand, the individual impacts of different urban underground structures, and on the other, their cumulative impacts on flow, using real case studies. Lastly, the works are placed in perspective regarding the integration of underground structures with the aim of operational management of an urban aquifer. The literature presents deterministic numerical modelling as a tool capable of contributing to this aim, in that it helps to quantify the effect of an underground infrastructure project on groundwater flow, which is crucial for decision-making processes. It can also be

an operational decision-aid tool for choosing construction techniques or for formulating strategies to manage the water resource.

Keywords Urban Groundwater · Groundwater flow · Underground constructions · Barrier effect · Groundwater budget

Introduction

Half of the world's population now lives in cities. The phenomenon of urbanisation is such that this proportion will reach 70 % (Un-Habitat 2008) by 2050. Despite this anticipated anthropic pressure, the protection of natural spaces remains a major challenge in the effort to limit horizontal urban sprawl. The influence of the two main constraints, anthropic pressure and property economics, leads (mechanically) to the vertical development of urban areas, particularly due to the potential provided by some subsoils to support urban growth. In parallel, urban subsoil is now recognised as a space rich in resources: available water, available space, geomaterials and geothermal heat (Li et al. 2013a), which play a vital role in ensuring sustainable land development (Goel et al. 2012; Maire 2011) but for which regulations remain wanting (Maire 2011; Foster and Garduño 2013). This results in a lack of coordination and planning in the exploitation of this space, illustrated by conflicts over use (Bobylev 2009), which can be detrimental to the different systems of the underground environment.

In particular, the resilience of groundwater resources appears to be a major issue. Although 40 % of the water distributed in the water supply networks of Europe comes from urban aquifers (Eiswirth et al. 2004), urban densification is leading to the construction of ever-deeper structures (Bobylev

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2009)—subways, building foundations, underground car parks, etc.—that interact with this resource. Several reviews in the literature have focused on the qualitative and quantitative pressures affecting urban aquifers. The review by Lerner (2002) presents the specific characteristics of urban groundwater recharge linked to artificial drainage networks, buildings and transport infrastructures. It also presents an account of the extent of anthropic contributions, in the form of leaks from underground pipes, to recharging urban aquifers. The review by Vazquez-Suñé et al. (2005) deals with notions specific to the study of groundwater in an urban context such as groundwater fluctuations caused by land and resource use, which are both sources of occasional and diffuse pollution of the urban system. The review by Rutsch et al. (2008) focuses on the different methods used to identify and quantify leaks from drainage networks, presenting the analytical solutions describing this phenomenon. The review by Schirmer et al. (2013) focuses on the factor of complexity of urban hydrogeology such as the heterogeneity of land-use and the presence of underground networks which lead to spatial and temporal variations in flows of water and contaminants.

Contrary to the qualitative and quantitative influences of water supply and drainage networks on groundwater, which have been the subjects of several studies, the role played by other underground structures such as tunnels and the foundations of large buildings is often excluded from urban hydrogeology studies and these aspects have not been covered by previous review papers. The interaction between groundwater and these structures can present risks and generate disturbances. Water drainage associated with underground structures can impact groundwater quality (Chae et al. 2008), and drainage generates piezometric depressions giving rise to areas of compaction (NSREA 1995; Yoo et al. 2009; Modoni et al. 2013). On the other hand, damage to buildings can be caused by the rise in groundwater levels resulting in flooding of lower building levels, excessive hydrostatic stress exerted on buildings, and the corrosion of foundations (Lerner and Barrett 1996). In addition, the heat island effect on groundwater due to urbanization is well observed for many cities around the world (Zhu et al. 2010; Taniguchi et al. 2009; Menberg et al. 2013). Geothermal heat can be regarded as a strategic urban resource (Lund et al. 2011; Herbert et al. 2013); since underground structures can significantly affect groundwater temperatures (Epting and Huggenberger 2013), this impact of urbanisation can be important. According to Benz et al. 2015, buildings reaching into or close to the groundwater generate a major part of the total anthropogenic heat flux received by groundwater.

Several authors have emphasised interest in overhauling the existing models of management applied to groundwater (Foster et al. 2013; Boreux et al. 2009; Vazquez-Suné and Sanchez-Vila 1999; Foster and Garduño 2013). Since 2010, the work resulting from the Deep City method (Li et al. 2013a,

b) has led to the first three-dimensional (3D) view of underground planning. This plan is based on the integrated management of all underground resources including groundwater; however, sponsors and developers must quantitatively take into account the interactions between groundwater and underground structures to plan the vertical development of the city so that it guarantees the qualitative and quantitative sustainability of groundwater resources.

According to Zhang et al. (2011), the lack of expertise and understanding of the interactions between different underground structures and groundwater remains an obstacle to the improvement of 3D urban planning. In particular, understanding groundwater flow in an urban context is the first step to improve qualitative and quantitative groundwater resource management. As a consequence, this review covers articles dealing with the quantitative impacts and interactions of underground structures (e.g. deep foundations, tunnels, underground car parks) on groundwater flow, in an urban context. In this paper, the impact on groundwater flow is considered as a modification of the flow system, or an evolution of water-table elevation, or a disturbance of groundwater budget, induced by an underground structure. Groundwater quality issues related to underground structures (e.g. sewer leakages and contamination) are not covered by this review.

This article is organised in four parts. The first part sets out the specific characteristics of urbanised aquifers and describes which underground structures are liable to disturb groundwater flow. The literature targeted is organised according to the structures concerned and the type of impact generated. The second part deals with studies on the obstacles that impede flow. The third part deals with studies on the contribution of underground constructions to the disturbance of the groundwater budget, generating recharge changes in urban aquifers. Lastly, the literature is placed in perspective regarding the attention given to underground structures and their impacts for the management of an urban aquifer.

Specifics of urbanised aquifers and the influence of subsoil use on groundwater flows

The issue of management inherent to the interaction between underground structures and groundwater first appeared in the scientific literature at the beginning of the 1980s when city centres were undergoing a process of deindustrialisation (Deveughèle et al. 1983; GCO 1982). At that time, a large number of water supply, industrial and mine pumps were decommissioned, leading to a rise of water levels in city centres, sometimes reaching several meters. This was the case in cities such as Barcelona (Spain), Berlin (Germany), Birmingham (UK), Budapest (Hungary), Houston (USA), Liverpool (UK), London (UK), Milan (Italy), Moscow (Russia), Paris (France), Lyon (France), Tokyo (Japan), and Bangkok

(Thailand) (Morris et al. 2003; Vazquez-Suné and Sanchez-Vila 1999; Yoshikoshi et al. 2009; Lerner and Barrett 1996). The subsequent rise in the groundwater level led to damage to existing buildings. According to Lerner and Barrett (1996), such damage to buildings included flooding of lower levels, excessive hydrostatic stress, and the corrosion of foundations. Questions on the risk of rising groundwater levels have been raised and several engineers have studied this hydrogeological problem to propose technical solutions that permit underground infrastructures to remain in place without detrimental effects associated with the coexistence of groundwater (Powers 1981; Cedergren 1997; Wong 2001). A list of the general principles employed for this purpose can be drawn up:

peripheral pumping intended to lower the groundwater level, dewatering of wells with drainage pumps, anchoring constructions with tie-rods, ballasting, and subhorizontal drainage.

Underground constructions can impact the flow of groundwater in two ways. They can either (1) act as an obstacle to the flow such that the hydrodynamic parameters of the aquifer are affected, or (2) disturb the mass balance of the flow system—defined in the meaning of Toth (1963)—in which the structure is located when the structure behaves as a Dirichlet, Neumann or Cauchy boundary condition. The installation of underground structures in an aquifer can lead to the following situations (Fig. 1):

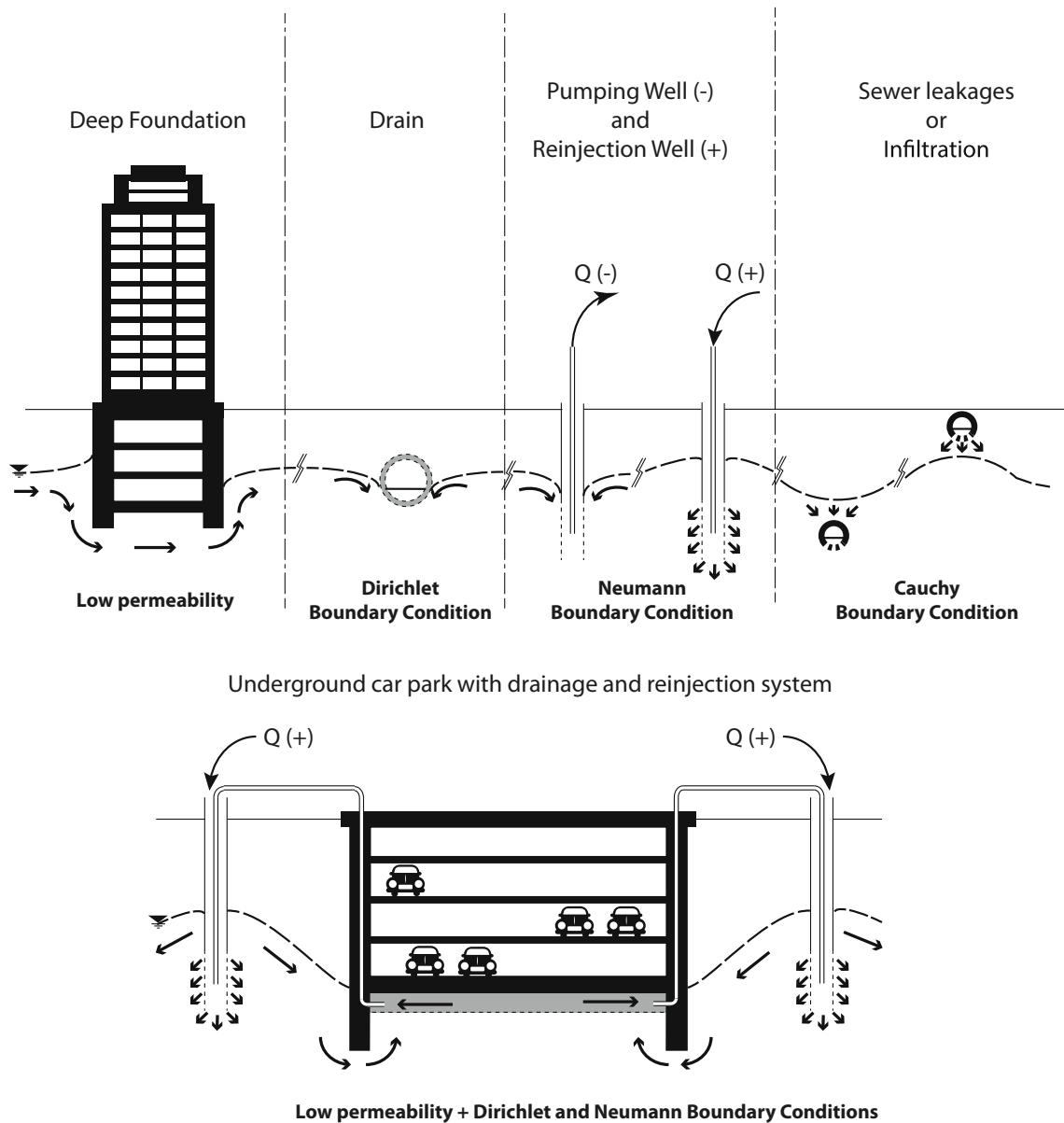


Fig. 1 Urban underground structures and their interaction with the water table. Assignment of the boundary conditions for resolving numerically several physical processes related to urban disturbances

- A modification of the environment’s hydrodynamic parameters such as the storage coefficient and the hydraulic conductivity. This is the case when a deep foundation is built.
- The introduction of a boundary condition, which can be described by three cases:
 - When an underground infrastructure is equipped with a drainage apron, it introduces a Dirichlet boundary condition (imposed potential).
 - When a pump shaft is installed, it introduces a Neumann boundary condition (imposed flow).
 - When a pipe network is built, it introduces a Cauchy boundary condition (imposed potential and clogging coefficient).
- The coupling of the first and second cases (see the aforementioned). This is the case of underground structures built on several levels and equipped with drainage systems. Their foundation and area covered locally modify the hydrodynamic parameters of the aquifer. Their drainage systems represent a boundary condition for the flow system studied.

The literature on the interaction between structures and groundwater is summarised in Table 1. It links a structure, and thus indirectly the use made of the urban underground space, with the disturbance associated with it in the literature. Studies are sorted by uses, infrastructures classes, and by the nature of the impact pointed out by authors: obstacles to flow or disturbance of groundwater budget.

According to Table 1, the largest number of works recorded concern linear constructions. The impact of a tunnel on the behaviour of the groundwater surface (water table) and the

contribution made by pipe networks to modifying the recharge of an urban aquifer are the two subjects giving rise to the largest number of studies in the literature (Table 1).

Table 1 shows that the structures can both modify flow and contribute to disturbing the groundwater budget. This is especially the case for tunnels. This dual impact can be explained by at least two factors:

- Different design techniques can be chosen to resist hydrostatic pressure due to the presence of groundwater. Infrastructures can be ballasted or anchored in the ground. They are thus considered as barriers to flows. When the hydrostatic pressure represents a technical or economic constraint exceeding the resistance of a ballasted or anchored structure, the latter is equipped with a drainage system. In this case, the infrastructures disturb the mass balance.
- The scale of the study capable of highlighting the disturbances of different types according to whether the author works on the flow system or on the structure area.

Two points of view can be distinguished in the literature dealing with the impacts of, and interactions between, infrastructures and urban groundwater. The first point of view considers the impact in the structure area (in the order of a hundred meters around the structure); the second point of view considers the impact in the urban area. In what follows, there is focus on the work identified in Table 1 devoted to the quantification of disturbances generated by underground infrastructures. In addition, there is focus on the scale of study. In the sections dealing with the impact in the structure area, the presented works focus on the impact in the proximity of the structure. In the section dealing with the impact in the urban area, impacts of structures are assessed in their overall flow

Table 1 Action of underground infrastructures on groundwater flow: obstacle to flow or disturbance of groundwater budget

Uses	Structures	Action on the natural flow of groundwater	
		Obstacle to flow	Disturbance of groundwater budget
Transport	Tunnels, galleries, subway lines	Ricci et al. 2007; Pujades et al. 2012; Deveughèle et al. 2010; Bonomi and Bellini 2003; Marinos and Kavvas 1997; Dassargues 1997; Merrick and Jewell 2003; Boukhemacha et al. (2015); Epting et al. (2008)	Butscher 2012; El Tani 2003; Yoo et al. 2012; Merrick and Jewell 2003; Dassargues 1997; Chae et al. 2008; Font-Capó et al. 2011; Boukhemacha et al. (2015)
	Underground carparks	-	Wong 2001
Networks	Water supply mains and manifolds, miscellaneous pipes	Rutsch et al. 2008	Karpf and Krebs 2011; Karpf and Krebs 2004; Ducommun 2010; Vázquez-Suñé et al. 2005; Lerner 2002; Rutsch et al. 2008; Boukhemacha et al. 2015
	Groundwater pumping	-	Larson et al. 2001
Housing/buildings	Basements of large buildings	Jiao et al. 2006; Ducommun 2010;	Ducommun 2010;

system and urban context. This distinction is made to distinguish, on one hand, the local and individual impacts of underground structures and, on the other hand, the role played by one or several underground structures at a decision-making scale. In addition, the second one allows the depiction of the cumulative impacts of underground structures on groundwater flow. All modelling approaches assessing the impact of underground structures on groundwater flow, and presented in this paper, are listed in Table 2 according to the structure of interest, the scale of the study, the main characteristics of the studied zone (e.g. conductivity, aquifer thickness), the modelling process (i.e. 2D/3D, finite elements/differences method, transient/steady) and the disturbances generated on the flow. If the author used field measurements to observe and quantify the impact of the underground structure of interest, it is mentioned.

Flow obstacles

Impact of flow obstacles in the structure area

Several studies analysed a flow obstacle in order to understand the higher piezometric levels upstream caused by the impermeable structure as well as the piezometric depressions downstream from it. Marinos and Kavvas (1997) and Deveughèle et al. (2010) presented several sensitivity tests to determine the factors of influence such as the depth of the infrastructure, the regional hydraulic gradient and the thickness of the aquifer, on the disturbance of the groundwater surface around the structure. The authors used numerical two-dimensional (2D) models.

The numerical models of Marinos and Kavvas (1997) used the finite element method. The authors tested a range of hydraulic gradients from 0.5 to 15 % and a range of tunnel summit depths from 0–1.5 m below the groundwater surface. The results of the simulations showed that the increase/decrease of piezometric elevation caused upstream/downstream of a circular tunnel is proportional to the height of the tunnel and the regional hydraulic gradient. For a range of hydraulic gradients from 0.5 to 5 %, and when the summit of the tunnel is located at the level of the groundwater surface, the groundwater level elevations generated are in the region of 1–10 % of the tunnel's height. For a range of hydraulic gradients from 10 to 15 %, and when the summit of the tunnel is located at the level of the groundwater surface, the elevations generated cover a zone defined by 35–55 % of the tunnel's height.

Deveughèle et al. (2010) modelled the additional loss of head generated by an impermeable gallery in the case of confined and unconfined groundwater. This entailed the difference between the final loss of head (in a context with structure) and the initial loss of head (in a context

without structure) between a point situated upstream of the structure and one at a point downstream of it. The authors first proposed an analytical solution to the problem of confined groundwater by making the analogy between the effect of a gallery and the effect of an impermeable barrier. This analytical solution depends on the thickness of the aquifer, the regional hydraulic gradient and a characteristic distance from the structure. The authors simulated the effect of an impermeable barrier within an aquifer with a length of 55 m, a thickness of 10 m and a hydraulic conductivity of 10^{-5} m s^{-1} . The radius of the gallery was varied from 10 and 50 % of the thickness of the aquifer and the hydraulic gradients tested were between 0.5 and 10 %. The authors then performed simulations of unconfined groundwater by representing a circular gallery in a 2D numerical finite differences model. The analytical solutions obtained confirmed the relation of linearity between the additional loss of head and the regional hydraulic gradient presented by Marinos and Kavvas (1997). In the case of the unconfined groundwater, the simulations gave the maximum zone of influence of the structure, which was about 3 times its diameter. These two studies (Marinos and Kavvas 1997; Deveughèle et al. 2010) observed disturbances of several centimetres in the region, when the hydraulic gradients were less than 1 %. For the same gradient, the maximum additional head loss was reached when the summit of the structure was located at the level of the groundwater surface.

Both studies provide a useful formulation of the barrier effect phenomenon and provide a sensitivity analysis to several parameters (e.g. hydraulic gradient, elevation of the infrastructure base); however, some points of discussion deserve to be noted. First, the regional hydraulic-gradient ranges tested in these studies seem too wide. In Table 3, approximations of the regional hydraulic gradient of several cities around the world have been reported. For several cities, urban hydraulic gradient appears to be lower than 0.5 %. This should be relevant to assess the barrier effect of impervious structures in a context of a hydraulic gradient between 0 and 0.5 %, i.e. lower than the tested ranges in the studies of Marinos and Kavvas (1997) and Deveughèle et al. 2010. Secondly, the 2D approach is a factor of overestimation of the barrier effect generated by a local impervious structure. The results can only be applied in 2D-geometry problems. Thirdly, the simulations have been run with upstream and downstream Dirichlet boundary conditions (imposed potential). This constrains the head over all the modelled area and is not representative of field conditions. In addition to that, the head constraints upstream and downstream are a factor for underestimation of the barrier effect because the barrier effect is bounded by the difference between upstream and downstream head constraints. In fact, when the potential is imposed, the flow is numerically reduced to respect the potential boundary

Table 2 Modelling approaches to assess the impact of underground structures. The method acronyms are respectively referring to horizontal/vertical (H/V) finite elements/differences (FE/FD) methods, i.e. HFEM, VFEM, HFDM, VFDM, in two dimensions (2D) or three dimensions (3D)

Underground structure	Generic or site specific	Aquifer characteristics	Studied area extent	Method	Field measurements	Transient (T) or Steady (S)	Disturbances	Reference
High-speed train tunnel	Florence (Italy)	Conductivity: 10^{-6} – 1.5×10^{-3} m s ⁻¹ Thickness: 35–40 m	36 km ²	HFEM-2D	No	T	Global head rise of several meters	Bonomi and Bellini 2003
Drainage network	Bucharest (Romania)	Conductivity: 2×10^{-4} – 2.7×10^{-3} m s ⁻¹	9 km ²	HFDM-2D	No	S	Contribution to the recharge: 53 % Contribution to the discharge: 76 %	Boukhemacha et al. 2015
Tunnel	Liège (Belgium)	Transmissivity: 7×10^{-3} – 1.4×10^{-1} m ² s ⁻¹ Thickness: 7 m	1.7 km ²	FDM-2D	No	T	Local maximum head drop: 1.6 m	Dassargues 1997
Tunnel	Generic	Conductivity: 10^{-5} m s ⁻¹ Thickness: 10 m	85 m	VFDM-2D	No	S	Local maximum head rise/drop: several centimetres (gradients < 1 %) Maximum zone of influence: 3 times the tunnel diameter	Deveughele et al. 2010
Several deep structures	Neuchâtel (Switzerland)	Conductivity: 10^{-4} m s ⁻¹ Thickness: 12 m	0.22 km ²	HFEM-2D	No	S	Global head drop of several meters around deep structures	Ducommun 2010
Highway tunnel construction	Basel (Switzerland)	Conductivity: 10^{-4} – 5×10^{-3} m s ⁻¹ Thickness: 15 m–35 m Transmissivity: 3×10^{-4} – 2×10^{-3} m ² s ⁻¹	9 km ²	FDM-3D	Yes	T	Flow discharged: 514 m ³ day ⁻¹ Reinjection 170 m ³ day ⁻¹	Epting et al. 2008
Subway line	Barcelona (Spain)	Conductivity: 6×10^{-6} – 6×10^{-5} m s ⁻¹ Thickness: 5–20 m Hydraulic gradients: 0.5–15 %	1 km ²	FEM-3D	Yes	T	Drawdown extent: 500 m Local maximum head drop : 2 m Flow discharged: 7,000–14,000 L day ⁻¹ for 100 m of line	Font-Capo et al. 2011
Deep foundations	Hong Kong (China)	Conductivity: 6×10^{-6} – 6×10^{-5} m s ⁻¹ Thickness: 5–20 m	1.4 km	VFDM-2D	Yes	T	Global head rise about 10 m	Jiao et al. 2006
Tunnel	Generic	Hydraulic gradients: 0.5–15 %	100 m	VFEM-2D	No	S	Local maximum head rise/drop: 1–10 % of the tunnel's height	Marinos and Kavvadas 1997
Tunnel	Sydney (Australia)	Not described	12 km ²	HFEM-2D	No	S	Maximum head rise/drop: 1.5 m (at distance of 100 m)	Merrick and Jewell 2003
Tunnel	Barcelona (Spain)	Transmissivity: 1.5×10^{-3} m ² s ⁻¹ Thickness: 22 m	200 m	FEM-2D	Yes	S	Local maximum head rise/drop: 8 m	Pujades et al. 2012
Railway station	Barcelona (Spain)	Transmissivity: 4×10^{-3} m ² s ⁻¹ Thickness: 12–20 m	200 m	FEM-2D	Yes	S	Local maximum head rise/drop: 1.2 m	Pujades et al. 2012
Subway line	Turin (Italy)	Conductivity: 10^{-5} – 10^{-3} m s ⁻¹ Thickness: 30–40 m	18 km ²	FDM-3D	No	S	Local maximum head rise/drop: 1 m	Ricci et al. 2007

Table 3 Approximation of the regional hydraulic gradient for several cities around the world

City	Country	Approximation of the regional hydraulic gradient	Reference
Paris	France	0.20 %	Deveughèle et al. 1983
Liverpool	United Kingdom	0.20 %	Lerner and Barrett 1996
Los Banos-Kettleman	California, USA	0.30 %	Larson et al. 2001
Turin	Italy	0.30 %	Ricci et al. 2007
Seoul	Korea	0.50 %	Chae et al. 2008
Liège	Belgium	0.80 %	Dassargues 1997
Florence	Italy	1.00 %	Bonomi and Bellini 2003
Basel	Switzerland	1.60 %	Epting et al. 2008
Barcelona	Spain	4.00 %	Font-Capo et al. 2011
Neuchâtel	Switzerland	8.00 %	Ducommun 2010
Hong Kong	China	15.00 %	Jiao et al. 2006

condition. It should be more appropriate to assign upstream and downstream Neumann boundary conditions (flow boundary condition). In this case, the flow would be imposed and the barrier effect would no longer be bounded.

According to Pujades et al. (2012), these two studies present too many limitations of applicability, which can be explained by the ranges of hydraulic gradients tested and by the choice of boundary conditions defined in the sensitivity test. Thus Pujades et al. (2012) proposed another way of formulating the problem of hydraulic barrier in the case of confined groundwater and applied it for different types of barrier. The authors wanted to focus on the long-term effects of infrastructures on the level of the groundwater surface. They proposed a five-step method to understand the disturbances caused by these different types of barrier on groundwater flow: semi-permeable barrier, partial obstruction of the aquifer, barrier with by-pass. The steps proposed in this study were the following:

- Study of the characteristics of the conceptual model and the flow equations. The hydraulic barrier effect is defined as an increase of loss of head along the streamlines caused by the loss of transmissivity induced by the underground construction.
- Exposure of the problem in a dimensionless form in relation to characteristic magnitudes such as the thickness and length of the aquifer and the identification of characteristic variables governing the solution.
- Formulation of a 2D numerical model to test the influence of characteristic variables.
- Construction of the form of analytic equation.
- Modulation of the terms of the analytic equation using multi-regression analyses. The function giving the best regression coefficient is selected.

This methodology was applied to a tunnel and to a railway station located under the city of Barcelona. The tunnel was considered as a partially penetrating infinite barrier. The railway station was considered as a fully penetrating barrier with a bypass. The confined aquifer in which the tunnel was located was composed of Quaternary sandy clays and Pliocene marls. The transmissivity of this aquifer was about $1.5 \times 10^{-3} \text{ m}^2 \text{ s}^{-1}$ and its thickness was 22 m at the level of the structure. The results of the analytical solution obtained for a partial obstruction of the aquifer gave a maximum local head loss value of 7.9 m downstream the structure. The ground measurements performed in the framework of this construction revealed a loss of head of 8 m. The shallow aquifer in which the railway station was located was composed of Quaternary deposits. The transmissivity of this shallow aquifer was about $4 \times 10^{-3} \text{ m}^2 \text{ s}^{-1}$ and its thickness ranged from 12 to 20 m. The results of the analytical solution obtained for a partial obstruction of the aquifer gave a maximum local head loss value of 1.19 m downstream the structure. The ground measurements performed in the framework of this construction revealed a loss of head of 1.2 m. In both cases, agreement was reached between the results of the analytical solution and the head losses observed locally by piezometry. This study demonstrated the major influence of the technical design of the barrier on the observed flow disturbances. In addition to that, Pujades et al. 2012 provide a method that allows one to numerically represent and discretize these different operating modes for groundwater modelling.

Impact of flow obstacles on the flow system in an urban area

Understanding the effect of a hydraulic barrier on the flow system makes it possible to predict the risks inherent to the evolution of the urban groundwater surface (Dassargues 1997;

Jiao et al. 2006) and evaluate the contribution of these obstacles to its vulnerability (Ducommun 2010).

The study by Dassargues (1997) focused on the installation of a new tunnel crossing the alluvial plain of the River Meuse in Europe. The author sought to predict the flood risk to the cellars of neighbouring detached houses associated with the raising of the groundwater level caused by the project. A numerical 3D finite differences model was used to evaluate its impact on the groundwater surface beneath an urban area covering 1.7 km². The mesh was refined close to the infrastructure so that the smallest cells did not exceed 25 m×25 m. The tunnel was integrated in the model by combining the impermeable cells next to the structure. Pumping tests gave the average hydraulic conductivity values of the alluvial deposit between 10⁻³ m s⁻¹ and 2×10⁻² m s⁻¹. The average thickness of this alluvial deposit was 7 m. Several simulations were performed in high and low water situations, with and without the infrastructure. The results of the simulations in the low water regime showed a rise in elevation in the region of several tens of centimetres liable to extend over several hundred meters around the structure. In the high water regime, the simulations showed that the infrastructure acted as a dam and that it maintained the piezometric levels stable for downstream hydraulics. This high water scenario is consecutive to flood conditions in both river sections crossing the studied area. Locally, the presence of a structure led to reducing the rise in elevation downstream caused by a high water episode by 1.6 m. The rise in elevation was reduced by 0.4 m at a distance of 300 m from the infrastructure. The structure attenuated the episode of rising groundwater. In this study, the authors highlight the transient influence of water-level conditions on the magnitude of the disturbances caused by an underground infrastructure; however, as specified in the section 'Impact of flow obstacles in the structure area', the assignment of Dirichlet boundary conditions upstream and downstream the modelled area is questionable. Constraining the head on the boundary of a studied area means that the underground infrastructure has a finite zone of influence included in the regional flow system. This assumption may be done when the characteristic dimension of the infrastructure is smaller by several orders of magnitude than the characteristic dimension of the modelled area, which is not the case in this study. To assess the water-table disturbance caused by the impervious structure, it should be more realistic to assume that the water flux crossing the studied area is maintained at the same value before and after the construction. The predictive aspect of the modelling approach allows one to forecast the impact of a large-scale underground structure taking into account the urban underground complexity.

The aforementioned work quantified the disturbances generated by a single obstacle to a flow. The study by Jiao et al. (2006) focused on the cumulated effects of obstacles, in this case the deep foundations of a district of Hong-Kong (China),

to a flow. This coastal area is subject to property pressure as space is limited by the sea. On one hand, the authors wanted to evaluate the role of land reclaimed from the sea, given that this area usually fulfils the role of final outlet for the aquifers, while on the other hand, the role of the foundations of large buildings on the functioning of the aquifer was evaluated. A vertical 2D numerical model was used to quantify the disturbances. The modelled perimeter is based on the water divide and on no-flow boundaries, which seems to be more realistic than hydraulic head constraints. The model did not take into account the discretisation of the foundations of large buildings. To represent the effect of the buildings, the hydraulic conductivity of the geological formation was divided by a factor from 14 to 20. The aquifer studied was composed of colluvial deposits and detrital volcanic rock with a thickness varying between 5 and 20 m. The hydraulic conductivity of the shallow formation of this aquifer varied from 6×10⁻⁶ to 6×10⁻⁵ m s⁻¹. It overlaid a zone of higher hydraulic conductivity 10⁻⁵ m s⁻¹ caused by the development of a crack network through a thickness between 2 and 3 m. The results of the simulations made it possible to compare water levels for three scenarios at two control points of the study zone.

- The first scenario corresponded to a natural state of the groundwater without deep foundations or land claimed from the sea.
- The second scenario corresponded to land claimed from the sea.
- The third scenario corresponded to land claimed from the sea with the presence of deep foundations.

The comparison of simulated water levels for each of these scenarios showed the impact of the foundations of large buildings. Indeed, in the third scenario, the water levels rose by about 10 m in comparison to the second scenario. This study demonstrated the cumulative impact of deep impervious structures on the flow system. Because the underground structures have not been discretised, this 2D vertical modelling approach allows one to understand the global effect of impervious structures on the flow. This method is particularly appropriate to assessing a global phenomenon (i.e. at the scale of an urbanized area).

Ricci et al. (2007) showed the effects of extending subway line 1 in Turin (Italy) on the alluvium water table. The geological context was Quaternary Riss glaciation and river deposits composed of silty sand with a thickness between 30 and 40 m. The hydraulic conductivity of this layer was between 10⁻⁵ and 10⁻³ m s⁻¹. This formation overlaid a river-lacustrine deposit of the Villafranchien period composed of silty clays with a thickness between 40 and 150 m. The hydraulic conductivity of this layer was between 10⁻⁸ and 10⁻⁶ m s⁻¹. The central axis of the subway line extension was located at a depth of about 18 m below the ground surface and its diameter was about 12 m. It partially obstructed groundwater flow: the

water table ranged from 12 to 15 m below ground level. An initial numerical 3D finite differences model at multi-kilometric scale was used to establish the hydrodynamic context of the subway line. A second 3D model was used to determine the disturbances caused by the tunnel and by the deep foundations of two stations built in cut-and-cover mode. The size of the elements of this model ranged from 5 to 25 m. A constant head boundary condition was assigned along the lateral upstream surface of the modelled zone. The results of the simulations in steady state showed local piezometric variations in the region of 1 m. The disturbances were in the region of a few centimetres several hundred meters from the structure. Here again, as for the study of Dassargues (1997), this boundary condition can be questioned because of the infrastructure characteristic dimension which has the same magnitude as the modelled area.

Considering the nuisance that changes in groundwater level can cause to constructions, Bonomi and Bellini (2003) worked on the impact of a high-speed train tunnel crossing the city of Florence (Italy) on the groundwater surface using numerical modelling. The 8-km-long tunnel crossed an alluvial deposit 30 m in depth and with a hydraulic conductivity between 10^{-6} and $1.5 \times 10^{-3} \text{ m s}^{-1}$. A horizontal 2D numerical finite element model covering a surface area of 36 km^2 was developed. The spatial discretisation of the domain was performed using regular cells of $50 \text{ m} \times 50 \text{ m}$. The structure was integrated in the model with semi-impermeable cells, like the model built by Dassargues (1997). The simulation was performed in transient state—the structure was installed at the beginning of the simulation—and permitted quantifying the impact of the tunnel up to 20 years after its construction. The results of the simulations showed that the maximum disturbance occurred at the central part of the structure and increased up to 20 years after its construction. The rises in elevation upstream of the structure and the reductions downstream could reach several meters and extend over several kilometres.

Merrick and Jewell (2003) sought to predict the compaction risks liable to occur during and after the construction of an urban tunnel in the city of Sydney (Australia). A horizontal 2D numerical model was developed to quantify the impact of the structure on the level of the groundwater. The steady-state model was used to test three alternative constructions: (1) an anchored infrastructure, (2) a drained infrastructure, and (3) a partially drained and anchored infrastructure. Three aquifer obstruction scenarios were tested in the case of the anchored infrastructure. The role of this structure as a hydraulic barrier was highlighted by a rise in elevation in the water level upstream of the structure and a reduction in its downstream level. For an obstruction in the region of 50 % of the aquifer, and under average climatic conditions, the results showed a maximum reduction in level of 1.5 m at distance of 100 m downstream of the structure. This represents half the average natural fluctuation of the groundwater level in this region. The infrastructure's zone of influence extended over a radius of about 600 m.

Disturbances of the mass balance

Mass balance disturbances in the structure area

The previous section showed that underground impervious infrastructures obstruct flows and are responsible for fluctuations in urban water level. Several techniques allow the construction of underground structures and involve other kinds of impact. Some of these techniques call on drainage systems to stabilise the structure or lining techniques in order to limit infiltration of water.

The review by Butscher (2012) proposed a synthesis of analytical and numerical solutions that predict infiltration of water from the saturated zone in circular tunnels. In particular, the study by El Tani (2003) established a precise solution for the permanent flow generated by a circular tunnel installed in a semi-infinite aquifer. According to Butscher (2012), analytical solutions are not well adapted to complex geological situations and the real conditions of the sites studied. The author recommends using deterministic numerical models to predict the drainage rate at different points of a tunnel-type infrastructure. Table 4 shows three tunnel support techniques with the hydrodynamic representation method required for the structure to be used in numerical models.

According to Butscher (2012) the use of numerical models to predict infiltration flows proves pertinent in the case of lined tunnels without a drainage layer. The difference in the hydraulic conductivity of the lining must be of several orders of magnitude compared with the hydraulic conductivity of the aquifer. Two methods of integrating the lining layer in the numerical model were compared. The first method consisted in defining a Cauchy boundary condition at the edge of the infrastructure. Defining the clogging coefficient facilitated the definition of the lining thickness. The second method consisted in representing the lining surrounding the structure by a layer with low permeability and defining a Dirichlet boundary condition at the edge of the structure. The representation of the lining layer by a Cauchy boundary condition and without discretisation under-estimates the flow in comparison to a Dirichlet boundary condition with discretisation.

Drainage (pumping) associated with these infrastructures causes a difference in hydraulic head between the inside and the outside of the lining layer. The resulting piezometric depressions can give rise to ground compaction in the area, which was observed in Oslo (Norway), Rome (Italy) (NSREA 1995), Seoul (Korea) (Yoo et al. 2009), and Bologna (Italy) (Modoni et al. 2013). Yoo et al. (2012) presented the link between the evolution of piezometry and the differential compactations observed when building a tunnel. Drainage can also cause the collapse of the tunnel construction face, possibly leading to a modification of surface structures and a costly interruption of construction (Font-Capo et al. 2011). Font-Capó et al.

Table 4 Hydrodynamic parameters and boundary conditions for the integration of a tunnel in a numerical model (according to Butscher 2012)

	Tunnel without lining	Tunnel with lining and drainage layer	Tunnel with lining and without drainage layer ^a	Tunnel with lining and without drainage layer ^b
Drainage	No	Highly permeable layer (discretisation)	No	No
Lining	No	Impermeable layer	Layer with low permeability (discretisation)	No discretisation
Boundary condition	Dirichlet	Dirichlet	Dirichlet	Cauchy

^a Anchored infrastructure^b Drained infrastructure

(2011) proposed an approach using 3D numerical modelling to predict infiltration flows into the tunnel during the construction of subway line 9 in Barcelona. The model permitted the prediction of infiltration flows discharged from the flow system ranging from 7,000 to 14,000 L day⁻¹ for 100 m of line. The authors also presented the evolution of the piezometry around the structure before and after the termination of construction. The maximum groundwater-level reduction observed was 2 m.

Other infrastructures crossing a flow system disturb the mass balance. To attenuate the mechanical stress on deep structures, one solution is to drain them. According to Wong (2001), this solution can be considered when the structure is installed in a shallow formation with low permeability; the author does not give an order of magnitude. In the Wong (2001) case, the drainage technique can limit the water infiltrating the structure and leads to limited reductions of the water level. Several carparks in the city of Lyon (France) are equipped with drainage systems. According to the local authorities, groundwater is drained at 13 structures to maintain their stability, at a total rate of about 20,000,000 m³ year⁻¹ (AERMC 2011). As far as is known at present, no study has yet focused on the disturbances generated locally by, or at the scale of, the flow system for such a density of infrastructures.

Mass balance disturbances on the flow system of an urban area

Urbanisation disturbs the balance of the flow systems of underlying aquifers, notably due to the modification of their recharge (Lerner 2002). The use of surface sealants, which reduce recharge, are offset by leaks from the water-supply network and the discharge of rainwater through soakaways (Vázquez-Suñé et al. 2005). These leaks amount to about 25 % of flows in transit (Lerner 2002). The case studies reported by Lerner 2002 mention a contribution capable of reaching 30–40 % of the total recharge of urban aquifers. Modification of the recharge of urbanised areas via leaks in networks represents a threat for groundwater quality (e.g.

micropollutants, pharmaceuticals and personal care products, pathogenic bacteria). Quantification of the interaction between groundwater and the sewer network has been the subject of several studies and is already well reviewed. In particular, Lerner (2002) worked on the identification and quantification of elements contributing to the recharge of an urban aquifer. Rutsch et al. (2008) focused on the leaks from urban drainage networks into the aquifer, and, conversely, Karpf and Krebs (2004) and (2011) focused on the drainage of urban aquifers caused by drainage networks.

At the scale of a conurbation, altering the recharge affects exploitation of the resource to supply water for human and industrial consumption. Hanasaki et al. (2008) gave several examples of regions in the world subject to severe water stress: the Sahel, South Africa, the centre of the United States, Australia, India, Pakistan and northeast China. The reduction of water levels following the over-exploitation of groundwater has impacts on the flow regime of aquifers (Wada et al. 2010), and on the quality of the resource (Larson et al. 2001). According to Larson et al. (2001), for each populated area, the maximum exploitable flow rate of the aquifer must be determined to avoid such consequences.

In addition to the over exploitation of groundwater, drainage networks can severely disturb the natural hydrogeological cycle of the groundwater and contribute to a reduction of water levels. Boukhemacha et al. (2015) developed a conceptual approach applied to a pilot area of 9 km² in Bucharest (Romania), which is a buffer zone for the lined Dâmbivita River; the work was dedicated to understanding the interaction between the flow of groundwater and underground development. The author paid particular attention to the interaction between groundwater and drainage networks. According to the authors, the choice of this pilot area was considered relevant because it includes the most important hydrological components of the city. The elements included in the conceptual approach are as follows:

- The structure of the aquifer system, which requires the development of a 3D geological model on the scale of the conurbation studied.

- The geometry of the drainage network and its interaction with the groundwater: exfiltration or infiltration.
- The network of subways and stations. For the Boukhemacha et al. (2015) study area, these infrastructures have a draining effect—water infiltrates into the structure—and an obstacle effect on the flow in comparison to the natural flow of the groundwater.
- The water supply network and its leaks.
- Groundwater recharging from rainwater.

These elements permitted building a numerical model to perform simulations of development scenarios and sensitivity tests. In particular, Boukhemacha et al. (2015) tested three water-level scenarios (low, intermediate and high) of the drainage network. For each scenario, computed hydraulic heads are compared with data from nine observation wells and the results were conclusive. The results of the simulations showed that the drainage networks contributed 53 % of the groundwater recharge and 76 % of its discharge. The authors succeeded in quantifying the contribution of manmade infrastructure elements on the natural hydrogeological cycle of the groundwater. Regarding groundwater infiltration into the sewer system, modelling results are compared to an estimated budget given by the water operator, at the scale of the city. The authors assumed a uniform distribution of infiltrated rates for the entire city. Finally, a good agreement is observed between the modelled and estimated budget.

To represent the vulnerability of urban aquifers to pollution, Ducommun (2010) developed an approach integrating the alteration of the recharge and taking into account the cumulative role of several underground structures. Part of the study consisted in understanding the role of infrastructures and underground developments in the vulnerability of urban aquifers. Working on the scale of the district of Maladière (Neuchâtel, Switzerland), the author built a horizontal 2D numerical model covering a surface area of 22 ha by integrating two types of anthropic element: the basements of large buildings and networks. The aquifer was Quaternary periglacial with an average thickness of 12 m, an average hydraulic conductivity of 10^{-4} m s^{-1} and an average specific storage coefficient of $1.3 \times 10^{-4} \text{ m}^{-1}$. The networks were integrated in the model by defining a Cauchy boundary condition. The average size of the finite elements was 6 m. The geometry of the structures was not explicitly represented in the mesh. The geometry of the deep foundations was integrated in the model in two steps:

- The first step consisted of removing the upper soil layers of the aquifer to the level of the base of the foundation, assigning a no-flow boundary condition on the overall foundation surface. Mechanically, this process locally reduces the transmissivity of the aquifer.
- The second step was to introduce the draining system of the foundation via a drainage boundary condition on the surface of the base of the infrastructure. The overall vertical surface of the deep foundation remained with a no-flow boundary condition. The author assumed that all the underground structures integrated in the model had a drainage system that disturbed the groundwater budget of the flow system.

Several scenarios were modelled, notably a basic scenario without an infrastructure, a scenario that integrated underground pipes, and a scenario that integrated underground pipes and deep foundations. The results of these simulations highlighted local hydraulic head disturbances capable of raising the groundwater level, or causing a depression, of several meters around the infrastructures. In this study, a major point is the geographical information system (GIS) representation of modelling results, including an accurate depiction of groundwater flow characteristics. In particular, modelling results are superimposed with urban structures data (e.g. buildings, drainage networks) which allows one to make operational recommendations regarding urban underground issues.

During the construction of the highway tunnel crossing the city of Basel (Switzerland), Epting et al. (2008) studied the development of a groundwater management system comprising a piezometric monitoring system, and a deterministic numerical hydrogeological model tested on five types of scenarios. The aquifer studied was a sedimentary alluvial plain of the Rhine with a thickness between 15 and 35 m and a hydraulic conductivity between 10^{-4} and $5 \times 10^{-3} \text{ m s}^{-1}$. A 3D numerical finite differences model was built to evaluate the scenarios.

- The 1st type of scenario was developed to compare the impacts of two engineering solutions on the groundwater flow. The first solution was to remove the residual water of an enclosure surrounding the structure. The second solution was to combine the first technique with the dewatering of the structure by pumping. Quantitative criteria linked to the spatial and temporal influence of piezometric disturbances were used to evaluate the scenarios: the local and regional disturbance of the hydrogeological regime, before and during the construction of the infrastructure; the quantitative conservation of the resource for industrial use; the conservation of resource quality; and the cost and technical feasibility. According to Epting et al. (2008), the first technique influences the local and global regime of the flow system during and after construction while the second technique has a greater influence but only during the construction phase. The results showed that the second solution had less impact.
- For the 2nd type of scenario, the distribution of pumping shafts and reinjection was optimised to limit conflicts of use, notably with the industrial area near the project studied.

- The 3rd type of scenario was used to compare the different groundwater resource management strategies; in particular the subsequent addition of a pumping shaft in the study area was tested.
- The scenario of type 4 tested the influence of groundwater regimes such as episodes of high and low groundwater levels.
- The 5th type of scenario tested worst-case accidental pollution events such as spills of contaminants.

This method was used to predict current and potential disturbances of an underground infrastructure on its flow system. For Epting et al. (2008), the integrated management of the resource during a major infrastructure project cannot be limited to local investigations. In this study, the modelling approach allowed the establishment of operational recommendations in terms of future urban underground planning and in terms of design technique choice.

Discussion

For the work described by Li et al. 2013a, b, managing the urban subsoil requires the integration of the different components composing it: geomaterials, geothermal energy, space and water. According to Vázquez-Suñé et al. (2005), the sustainable management of groundwater requires the integration of elements liable to modify the quantitative and qualitative regime of the groundwater. In an urban framework, this implies knowledge of the underground developments and land use that complexify the groundwater budget of flow systems, vary water levels, and contaminate the resource punctually or in a diffuse way.

This article shows that underground structures have two types of impact on underground flows (Table 1). They can (1) impede the natural flow of the groundwater or (2) disturb the groundwater budget of the flow system. The literature studied in this review highlights that these disturbances can extend over an area exceeding the scale of the structure. The timescale of these disturbances can cover more than a decade. These disturbances jeopardise the qualitative and quantitative sustainability of the resource, and lead to the development of risks and nuisances: qualitative and quantitative threat to the water supply, flooding risk, settlement risk, and influence on the geothermal potential of the urban aquifer. Thus, it can be concluded that the impacts of underground infrastructures on flows must be integrated in any attempt to manage the urban subsoil. Several approaches can be adopted to understand these impacts: piezometric observations, systemic studies, and deterministic studies using numerical models.

Using piezometry permits the real-time acquisition of qualitative and quantitative monitoring data; thus, it plays a major role in underground water-resource management. Piezometric

measures permit the observation of local hydraulic disturbances generated by a structure occupying underground space (Font-Capó et al. 2011; Yoo et al. 2012). In addition to that, as shown in the Table 2, several authors used field measurements to verify modelling results and to directly observe the impact caused by underground structures on groundwater flow; however, the interpretation of these data requires precise, updated and centralised knowledge of the underground environment (Deveughèle et al. 1983).

Systemic studies allow linkage of the different components of the complex system represented by the urban subsoil. They provide managers with an advantage insofar as it provides them with a decision aid tool at the strategic level of land development (Chen et al. 2005; Li et al. 2013a). However, this approach considers the urban subsoil as a whole, and it is not adapted to the operational management of an urban area.

The literature presents deterministic numerical modelling as a tool that contributes to the management of an urban aquifer. It permits quantifying the impacts generated by infrastructures on groundwater flow. These results can be used to develop analytical solutions and predict disturbances (Pujades et al. 2012). Deterministic numerical modelling can also be used to quantify the effect of an underground infrastructure project on flows (Ricci et al. 2007; Merrick and Jewell 2003; Dassargues 1997; Bonomi and Bellini 2003). It can provide a decision aid tool for choosing construction techniques (Epting et al. 2008) or for formulating a resource management strategy (Larson et al. 2001). In addition to that, the literature shows that numerical modelling is often used as a means of anticipating the disturbances caused by underground infrastructure projects, in their order of construction in areas. The impact of an infrastructure or the variants of an infrastructure project on a flow is quantified individually. Regarding this point, Table 2 shows that tunnel impacts are the most reported for various scales (i.e. from the scale of several meters to the scale of several kilometres). Only a few studies deal with the impact of other underground structures even if the cumulative impact of impervious structures has been shown as significant at the scale of the city (Jiao et al. 2006).

The reflection developed in the framework of this article led the authors to think that a sustainable method of managing the resource would be to improve understanding of the interactions between the anthropic and natural elements of the urban subsoil with a view to formulating a 3D organisation chart of the area concerned. Such a planning diagram should identify the zones strategic for urban underground development and for groundwater flows.

To do this, deterministic numerical modelling can be used to describe the flow systems of an urban area. The role of urban developments in the organisation of these flow systems must be quantified. The cumulated impacts of underground structures on flows could therefore be described operationally by decision-makers. Epting et al. (2008), Ducommun (2010)

and Boukhemacha et al. (2015) show the potential provided by numerical modelling to quantify the cumulated impacts and interactions of underground structures in a heterogeneous underground space subject to complex hydrodynamic phenomena. Moreover, the accurate depiction of urban groundwater flow systems, as it can be performed with 3D deterministic modelling, remains an important step to develop relevant spatial analysis to sustainably exploit urban underground resources. A study focused on understanding the cumulated impacts of infrastructures on the flow is in progress (Attard et al. 2015). This study plans for the development of a 3D numerical model on the scale of the city of Lyon (France) to understand the impacts and interactions of different types of structure: subway lines, the foundations of large buildings, structures equipped with drainage systems such as underground carparks and pumping systems. Lastly, the capacity of decision-makers to understand flow systems, how they function, and their response to the installation of new structures in the territory they manage will form the basis for the operational management of urban groundwater resources.

Summary and conclusions

Urban underground is a complex system with many operating man-made infrastructures (e.g. underground buildings, subway lines, sewer networks, heat pump schemes). These structures disturb the natural flow and quality of groundwater. The literature shows that lots of studies deal with the individual impacts of underground structures on groundwater flow. Regarding the structure area, several approaches developed sensitivity 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. Regarding the urban area, modelling approaches showed the large spatial and temporal extent of groundwater disturbances generated by underground structures.

This review points out the major role of modelling approaches in the quantification of these disturbances. First, this paper shows how to numerically represent the hydrodynamic behaviour of an underground structure with appropriate material properties and boundary conditions (see Fig. 1), which is a crucial step in assessing the impact of an underground structure on groundwater flow with a deterministic modelling approach.

For both approaches distinguished in this paper (i.e. regarding the structure area or the urban area), several lessons can be learned:

- Vertical 2D approaches allow the quantification of local disturbances caused by impervious tunnels on flow with an accurate depiction of groundwater flowpath modification. These approaches also allow one to understand the global effect of impervious structures on water-table elevation.
 - Horizontal 2D approaches allow a spatial depiction of flow systems. In addition, modelling results can be superimposed with spatial urban data to provide, with a spatial analysis, management recommendations regarding underground planning issues.
 - 3D approaches allow the quantification of local disturbances caused by underground structures on flow with an accurate depiction of groundwater flowpath modification. This approach is particularly relevant to assess the interaction between groundwater and structures during the construction. In addition, 3D approaches allow a spatial depiction of flow systems horizontally and vertically. The approach is particularly relevant to assess the impact of structures with complex geometry and with a complex hydrogeological context (e.g. layered aquifer, faults, underground structure reaching superimposed aquifers).
- The use of finite elements methods is a major asset for the accurate depiction of flow disturbances. It allows one to take into account the horizontal and vertical geometry of underground structures, and to take into account the complex operating mode (e.g. drainage system and reinjection) of underground structures which could have a major influence on disturbances.
- In the next few years, the cumulative impact of underground structures on urban groundwater will be of increasing interest. The future stakeholders will have to combine the vertical development of a city and sustainable groundwater management. This challenge requires a management of risks inherent to the evolution of urban groundwater flow in terms of quantity and quality,
- According to the authors of this review, the chain-reaction generated by the modification of urban groundwater flow on groundwater quality and quantity have to be considered. For a better understanding of the qualitative and the quantitative influence of underground structures on groundwater, the first step should be to focus on the flow in urban areas. Several recommendations are proposed for future research in urban hydrogeology regarding the improvement of urban underground planning:
- Sensitivity analysis should be made to classify the impacts regarding structures and design techniques. The underground structure-affected zone (USAZ) should be defined using flow parameters (e.g. hydraulic head, Darcy velocity, groundwater age).
 - The cumulative impacts of underground structures have to be assessed at the decision-making level, and regarding hydrogeological constraints. Three-dimensional modelling investigations should be done to quantify such an impact. In particular, multi-scale approaches could be relevant to represent complex phenomenon at larger scales.

- The 3D-modelling approach could contribute to define the potential state of urban aquifers in terms of flow. The accurate depiction of groundwater flow, and the understanding of the influence of underground structures, could help to identify pertinent natural and anthropic contexts for the development of the urban underground by a spatial analysis.

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