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Deterministic modelling of the cumulative impacts of underground structures on urban groundwater flow and the definition of a potential state of urban groundwater flow: example of Lyon, France

Guillaume Attard^{1,2}, Yvan Rossier³, Thierry Winiarski¹, Loann Cuvillier¹, Laurent Eisenlohr²

Abstract Underground structures have been shown to have a great influence on subsoil resources in urban aquifers. A methodology to assess the actual and the potential state of the groundwater flow in an urban area is proposed. The study develops a three-dimensional modeling approach to understand the cumulative impacts of underground infrastructures on urban groundwater flow, using a case in the city of Lyon (France). All known underground structures were integrated in the numerical model. Several simulations were run: the actual state of groundwater flow, the potential state of groundwater flow (without underground structures), an intermediate state (without impervious structures), and a transient simulation of the actual state of groundwater flow. The results show that underground structures fragment groundwater flow systems leading to a modification of the aquifer regime. For the case studied, the flow systems are shown to be stable over time with a transient simulation. Structures with drainage systems are shown to have a major impact on flow systems. The barrier effect of impervious structures was negligible because

of the small hydraulic gradient of the area. The study demonstrates that the definition of a potential urban groundwater flow and the depiction of urban flow systems, which involves understanding the impact of underground structures, are important issues with respect to urban underground planning.

Keywords Urban groundwater · Groundwater management · Deterministic modeling · Underground constructions · France

Introduction

According to Un-Habitat (2008), half of the world's population now lives in cities and urbanisation is such that this proportion will reach 70 % before 2050. The anthropic pressure leads to the vertical development of urban areas, particularly bearing in mind the potential for urban growth provided by the subsoil. This vertical development leads to the construction of ever-deeper structures (Bobylev 2009): subways, building foundations, underground carparks, etc. that can interact with other underground resources such as available water, available space, geomaterials and geothermal heat (Li et al. 2013a, b). According to Maire (2011) and Foster and Garduno (2013), the regulation of urban underground is lacking and results in conflicts of use (Epting et al. 2008; Bobylev 2009), detrimental to the different systems of the underground environment.

Particularly, the resilience of groundwater resources appears to be a major issue. In Europe, 40 % of the water distributed in the water supply networks comes from urban aquifers (Eiswirth et al. 2004). The interaction between groundwater and underground structures has been shown to be responsible for risks and disturbances. Underground structures can impact groundwater quality (Chae et al. 2008), drainage systems can generate piezometric depressions giving rise to compaction in places

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(NSREA 1995; Yoo et al. 2009; Modoni et al. 2013), and damage to buildings can be caused by a rise in groundwater levels (Lerner and Barrett 1996).

These risks and disturbances justify the interest in overhauling the urban groundwater management model (Foster et al. 2013; Boreux et al. 2009; Vazquez-Suné and Sanchez-Vila 1999; Foster and Garduno 2013); however, a better understanding of the interaction between underground structures and groundwater is needed to improving three-dimensional (3D) urban planning. A recent review focused on the impact of underground structures on the flow of urban groundwater (Attard et al. 2016). That review found that underground constructions (e.g. impervious structures, pumping wells, drainage systems) can have an impact on the flow of groundwater in two ways: (1) as an obstacle to the flow, or (2) as disturbance to the mass balance of the flow system in which the structure is located when the structure behaves as a Dirichlet, Neumann or Cauchy boundary condition. In addition, the review showed that only a few studies (Jiao et al. 2006; Epting et al. 2008; Ducommun 2010; Boukhemacha et al. 2015) have dealt with the cumulative impacts of several underground infrastructures; in other words, these impacts on urban flow systems are more or less ignored.

The aim of the study reported here is to quantify the cumulative impact of underground structures on the flow of urban groundwater. These impacts have been studied at the scale of

the city of Lyon (France) by a deterministic modeling approach in steady state. First, this paper focuses on the cumulative impact on the structure of urban flow systems and on the elevation of the water table in the urban area. Secondly, it focuses on the role played by different technical designs in the impact on the structure. Finally, transient simulation results are presented to assess the temporal stability of flow systems regarding high and low water level situations.

Materials and methods

Area studied and underground structures

An area in the city of Lyon (France) ($45.75^{\circ}\text{N}/4.85^{\circ}\text{E}$) was chosen, to study the cumulative impact of underground structures on groundwater flow. Lyon has great potential for urban underground development in the light of the criteria proposed in Li et al. (2013a, b)—i.e. subsurface geotechnical quality, groundwater quality, geothermal energy, geomaterial quality, urban population, living density and gross national product (GDP) per capita. In practice, this potential is reflected by the economic attractiveness of Lyon (Carpenter and Verhage 2014) at the European scale.

East Lyon is a filled area of the Rhone Valley that collapsed during the Tertiary period (Fig. 1a). During the Quaternary period,

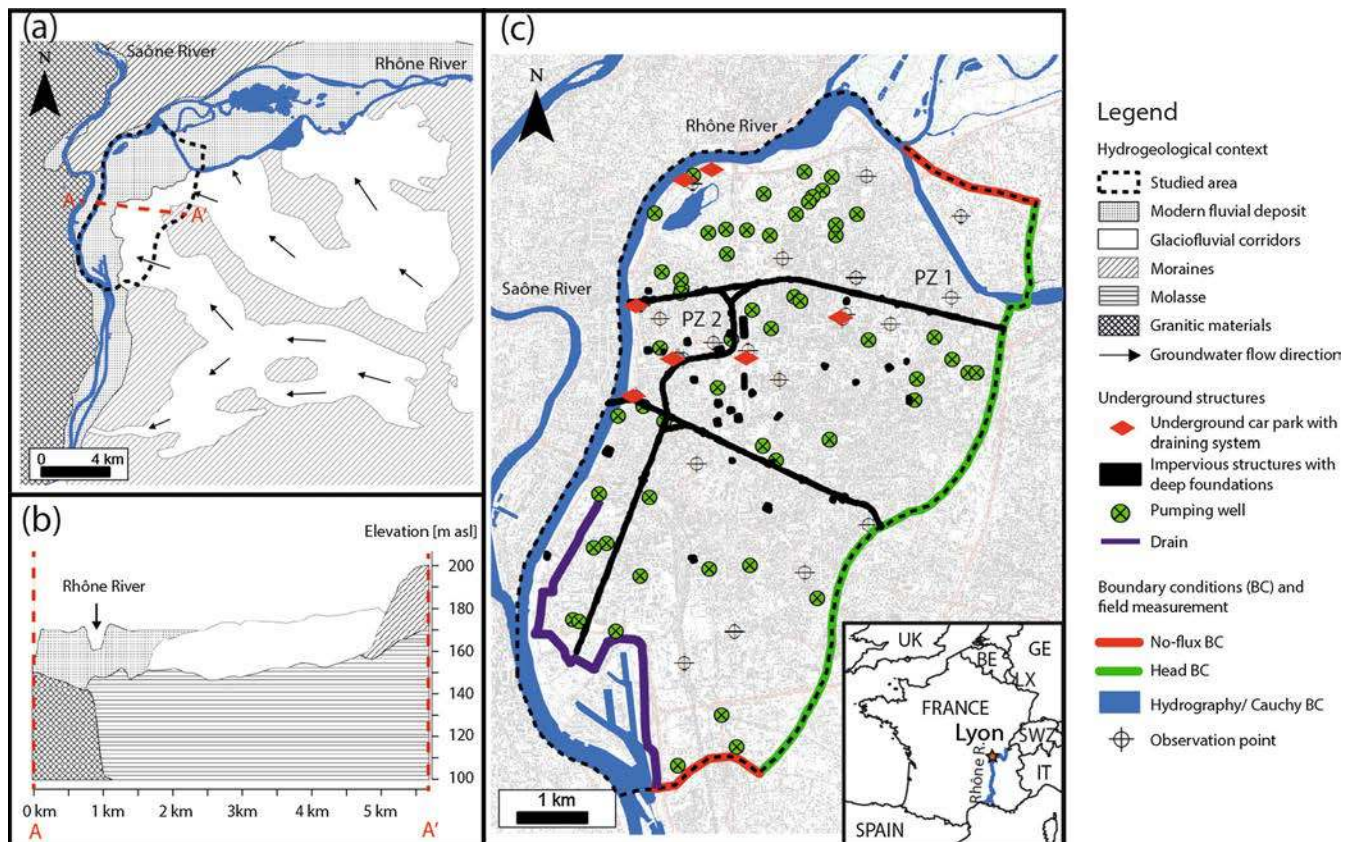


Fig. 1 Site description: a–b hydrogeological context, and c underground structures and boundary conditions

the successive advances and retreats of the Rhone glacier from the Lyon outwash lobe during different glaciations led to the deposit of materials of glacial origin (moraines, glaciofluvial sediments, loess) on the molasse dating from the Miocene period (Mandier 1984). The relief stemming from Quaternary origins is marked in particular by radial morainic hills between which the melt waters of the last glacial maximum produced glaciofluvial corridors (Mandier 1984 and Franc 2005). The modern fluvial deposit of the urban area is around 25 m thick and overlies the molasse layer, which is around 150 m thick (Fig. 1b). In the more densely populated districts of the area studied, the water table is around 5 m below the surface. The alluvial aquifer is recharged upstream by groundwater flow coming from two eastern glaciofluvial corridors and on the upper surface by effective infiltration and network (i.e. water supply and sewage) leakages.

The area studied has been delimited by a piezometric map established by Gudefin and Rousselot (1974). The surface area studied is 44 km². The eastern upstream boundary is formed by a potential isoline. The northern boundary is formed by a no-flux limit and the border of the Rhone River. The western boundary is formed by the border of the Rhone River. The southern boundary is formed by the outlet of the alluvial aquifer (i.e. the Rhone River section) and by a no-flux limit.

The underground structures of the area studied have been classified into four groups: (1) drains; (2) hydraulic barriers, for infrastructures with impervious properties like deep concrete foundations; (3) pumping wells; and (4) impervious structures with drainage systems like deep structures equipped with a drainage layer and reinjection wells. All the structures taken into account in the present paper are listed below (Fig. 1c):

- Three subway lines and 30 impervious structures act as hydraulic barriers. The elevations of the impervious underground structures were taken into account considering the number of underground floors and assuming a depth of

2.5 m per floor. Subway base-slab elevation was taken into account considering the axis-line elevation and the thickness of cut-and-cover tunnels. These subway lines are built in the modern fluvial deposits and in layers of glaciofluvial deposits.

- Seven underground car parks act as impervious structures with drainage systems. These drainage systems are designed to prevent the uplift of the infrastructures. The pumping rate generated can reach more than 20,000 m³ d⁻¹ for a single car park. The seepage flow can be reinjected close to the park with reinjection wells. When reinjection is not possible, the seepage flow is discharged into rivers or sewer networks. According to public data from AERMC (2012), these infrastructures pumped more than 20,000,000 m³ in 2012. These structures were built with diaphragm walls which penetrate the molasse layer of the aquifer by at least 5 m.
- A drain had been built in the south of the study zone. This infrastructure has two purposes. The first was to lower the level of the groundwater due to the construction of a dam downstream of the zone studied. The second was to provide enough water supply to industries located in the south of this zone. The drain is located in the layer of modern fluvial deposits.
- Fifty-five pumping wells without reinjection into groundwater were recorded. These pumping wells are all located in the modern fluvial deposits and in the layers of glaciofluvial deposits. These pumping wells are mainly dedicated to industrial cooling systems.

The main characteristics of underground structures are summarized in Table 1. A column is dedicated to the numerical description of these structures in the numerical model including the boundary conditions used: Dirichlet BC for seepage face and Neumann BC for pumping or reinjection devices.

Table 1 Underground structures in the area studied

Underground infrastructures	Infrastructure class	Depth range (m)	Pumping rate (m ³ d ⁻¹)	Numerical description
Subway lines	Hydraulic barrier	10–30	–	Low permeability, $K = 1 \times 10^{-8} \text{ m s}^{-1}$
Impervious structures	Hydraulic barrier	5–30	–	Low permeability, $K = 1 \times 10^{-8} \text{ m s}^{-1}$
Car parks with drainage systems	Structure with drainage system	5–30	13–22,800	<i>Structure:</i> Low permeability $K = 1 \times 10^{-8} \text{ m s}^{-1}$ <i>Drainage layer:</i> Dirichlet BC <i>Reinjection well:</i> Neumann BC
Drain	Drain	5–10	–	Dirichlet BC
Pumping wells	Pumping well	–	1.5–27,500	Neumann BC

BC boundary condition, K hydraulic conductivity

Experimental modelling design

Cumulative impact of underground structures

The “actual state” and the “potential state” of urban groundwater flow were simulated to assess the cumulative impact of underground structures on groundwater flow:

- The “actual state” scenario consisted of the modeling of the urban groundwater flow with all the known underground structures. The simulation was performed in steady state and the scenario was calibrated (see the section ‘Numerical representation of underground structures’).
- The “potential state” scenario consisted of modelling the urban groundwater flow without underground structures. The simulation was performed in steady state. The ‘potential state of urban groundwater bodies’ is a concept introduced by Epting and Huggenberger (2013). In that case, the potential state of groundwater was derived in order to assess the heat island effect in urban groundwater bodies. To perform this simulation, all the underground structures from the “actual state” scenario were removed except the drain. The drain was not removed because of its major role in structuring the flow. This scenario was not calibrated because of the unreal character of the potential state.

Computing the comparison between these two scenarios resulted in the cumulative impact of underground structures on the flow with respect to the structure of the intermediate flow systems and the water-table elevation. A flow system is defined as the catchment connected to an outlet by groundwater flow streamlines (Toth 1963). According to Toth (1963) three types of flow systems may occur: local, intermediate, and regional. In this paper, the focus is mainly on the intermediate scale because it matches the scale of the urban area. The intermediate flow systems have been distinguished according to the starting points of flow streamlines: glaciofluvial corridors, Rhone River, and the outputs are the Rhone River, pumping devices, and drains.

Role played by impervious structures and structures with drainage systems

An intermediary state was simulated to assess the contribution of impervious structures (i.e. deep foundations, subway lines) and structures with drainage systems (i.e. underground car parks). In this scenario, impervious structures were removed from the model. The simulation results were compared with the actual state of the groundwater flow.

Stability of flow systems during high/low water level episodes

To assess the temporal stability of flow systems quantified in the actual state scenario, a transient simulation was performed according to the temporal data of 2012 (i.e. direct recharge, river water levels, upstream boundary conditions). The flow systems were depicted under low water conditions according to the computed data for March 31, 2012. The flow systems were depicted under high water conditions according to the computed data for June 29, 2012. The locations of flow system boundaries of both scenarios were compared. All the simulations performed, with their main characteristics, are listed in Table 2.

Hydrogeological modelling of the Lyon area

Modelling process

The modeling process consists of solving the diffusivity in the porous media equation for the entire area studied. This process requires delimiting the area studied (Fig. 1c) with an assignment of material properties (see section ‘Material properties’) and boundary conditions (see section ‘Boundary conditions’).

The FEFLOW® code (Diersch 2013) was used to solve the diffusivity equation using the finite element method. A horizontal mesh was applied including the discretization of rivers and infrastructure edges using a triangle algorithm (Shewchuk 2005). Vertical discretization was based on geological interfaces and by adding intermediate slices to allow the inclusion of infrastructures for each geological layer. 1,044,344 nodes and 1,813,091 tri-linear triangular 6-noded prism elements were generated. The horizontal size of the elements ranged from several centimeters near structure edges to several tens of meters. Simulations 1, 2 and 3 (see Table 2) were run in steady state. Simulation 4 (Table 2) was run under transient conditions from 1 January 2012 to the 31 December 2012 with an initial time step of 1×10^{-6} d.

Material properties

A 3D geological model was developed at the scale of this area using a geological map, 1,464 drilling data (BRGM 2013), several geological cross sections (Mongereau 2010; David et al. 1979; Gudefin 1971, Gudefin and Rousselot 1974), a digital terrain model (GrandLyon 2013), and the bathymetry of the Rhone River (Voies Navigables de France, personal communication, 2013). These were used to build the 3D geological model with RockWorks. Four main layers were extracted from this geological investigation: modern fluvial deposits, glaciofluvial deposits, moraines, and a molasse layer (Fig. 1). These four layers overlie a granitic basement which is the bedrock. Although the main flows pass through the modern fluvial deposits and the layers of glaciofluvial deposits, the molasse layer had to be taken into account because several

Table 2 Simulation characteristics

Simulation No.	Simulation name	Goal	Underground structures	Steady–transient (S/T)	Field measurement
1	Actual state of urban groundwater flow	Depiction of actual flow systems. Computation of water-table elevation	-Impervious structures -Pumping wells -Drain -Underground car parks	S	Yes
2	Potential state of urban groundwater flow	Assessment of impact of underground structures on groundwater flow, plus a comparison with the actual state of urban groundwater flow	-Drain	S	No
3	Intermediary state	Quantification of the role played by different kinds of underground structures	-Pumping wells -Drain -Underground car parks	S	No
4	Actual high and low water level conditions	Assessment of the temporal stability of flow systems	-Impervious structures -Pumping wells -Drain -Underground car parks	T	Yes

underground infrastructures reach this geological formation. The inclusion of this geological formation in the model was necessary in order to reproduce the correct operation of the draining structures during the pumping and reinjection process. Before calibration, homogeneous and isotropic material properties were associated with each geological layer. The hydraulic conductivities and storage coefficients taken from the literature are shown in Table 3.

Boundary conditions

A Dirichlet boundary condition (BC) was applied to the upstream contour according to the mean value of hydraulic heads measured in 2012. Along the upstream contour, the value ranged from 166 m above sea level (asl) to 168 m asl for the actual state simulation. Several studies have shown the large spatial extent of the impact generated by underground structures (Dassargues 1997; Epting et al. 2008; Merrick and Jewell 2003; Ricci et al. 2007). Consequently, the cumulative effects of all the underground

structures taken into account for this work on the hydraulic head distribution were expected to reach the upstream contour. Then, it was more relevant to assume that the total water inflow remained unchanged between the actual and the potential state than to impose the upstream hydraulic head. So, preliminary computations were run in order to adjust the upstream hydraulic head BC in the potential state and in the actual state, in order to maintain the same groundwater inflow. Finally, for the potential state simulation, the boundary condition of the upstream contour was increased by 0.5 m in order to reproduce the same inflow as in the actual state simulation.

Downstream, a Dirichlet BC was applied to the drain according to the elevation of this infrastructure, from 152.2 to 158.3 m. The drainage layers of the structures were also defined with a Dirichlet BC. For the transient scenario, the upstream hydraulic head was assigned according to a multiplier function with a time step of 10 days (Fig. 2a). In transient models, all boundary conditions can be modified by applying a time series as a multiplier function. The values of the time

Table 3 Material properties of the layers studied (Nicolas et al. (2004); Collin et al. (1973); Brenot et al. (2009))

Layer	Hydraulic conductivity before calibration (m s^{-1})	Hydraulic conductivity after calibration (m s^{-1})	Storage coefficient (%)
Modern fluvial deposits	1×10^{-3}	1×10^{-4} – 2×10^{-3}	15
Glaciofluvial deposits	2×10^{-3}	8×10^{-4} – 4×10^{-2}	15
Moraines	1×10^{-4}	5×10^{-4}	15
Molasse	1×10^{-5}	6.8×10^{-6} – 9.4×10^{-5}	2

series used for the multiplier function are multiplied with the values of the boundary condition at each time step of the simulation (Diersch 2013).

A Neumann BC was applied to the upper surface of the model to reproduce recharge from precipitation and network losses. Net recharge from precipitation (Fig. 2b) was calculated using the meteorological data of 2012 and applying the model of Brochet and Gerbier (1974) where net recharge is derived from the evapotranspiration estimation. An average of 150 mm year^{-1} was applied to vegetated areas covering 7.4 % of the area studied. Net recharge was computed from 1997 to 2012 (see Table 4). According to Table 4, the annual direct recharge mean value is 170 mm and the standard deviation is 70 mm. Network losses were calculated assuming a leakage factor for network losses of 10 % and considering a flow of $100,000,000 \text{ m}^3 \text{ year}^{-1}$ into the networks. Losses represent an average of 416 mm year^{-1} . These losses were applied homogeneously across the upper surface. For the transient scenario, direct recharge was assigned according to a multiplier function with a time step of 10 days (Fig. 2b). The transient influence of network losses was not taken into account in the transient scenario.

A Cauchy BC was applied to represent interactions between rivers and groundwater. For the transient scenario, river-water level was assigned according to a multiplier function with a time step of 10 days (Fig. 2c). The boundary conditions of the steady “actual state” scenario are summarized in Table 5. The clogging coefficients of rivers crossing

the area studied are based on a regional study by Nicolas et al. (2004).

Numerical representation of underground structures

According to Attard et al. (2016), the installation of underground structures in an aquifer can lead to the following situations (Table 5):

- 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. This is the case:
 - when an underground infrastructure is equipped with a drainage apron, so it introduces a Dirichlet boundary condition (imposed potential)
 - when a pump shaft is installed, so it introduces a Neumann boundary condition (imposed flow)
 - when a pipe network is built, so it introduces a Cauchy boundary condition (imposed potential and clogging coefficient)
- The coupling of a modification of the environment’s hydrodynamic parameters and the introduction of a boundary condition. This is the case of underground structures

Fig. 2 Multiplier function used in transient scenario for **a** the upstream hydraulic head boundary condition (BC), **b** direct recharge and **c** water levels in Rhone River. *Black dots* show the calculated value every 10 days. *Black lines* show the linear interpolation between two time steps. The *vertical grey lines* show the rainfall for a period of 10 days [mm] (**b**)

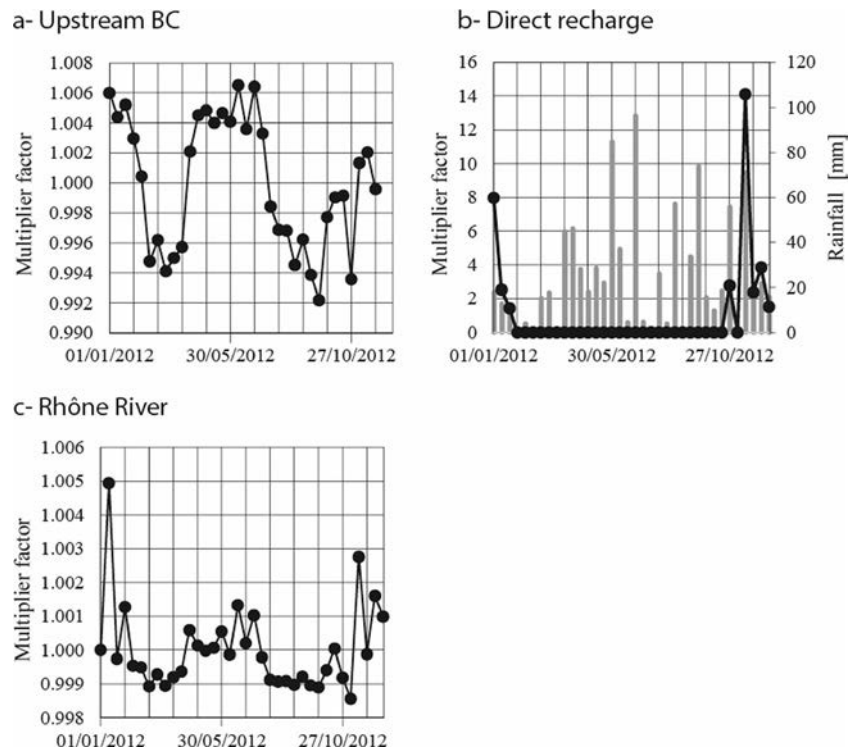


Table 4 Direct recharge (by year) from 1997 to 2012 calculated using meteorological data and applying the model of Brochet and Gerbier (1974). For all years, the mean value is 170 mm and the standard deviation is 70 mm

Year	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Direct recharge [mm]	112	104	247	204	133	288	241	195	122	158	26	150	191	166	104	150

built on several levels and equipped with drainage systems. Their foundation and the area covered locally modify the hydrodynamic parameters of the aquifer. Their drainage systems represent a boundary condition.

Consequently, all the structures were integrated in the 3D numerical model with their geometry. A hydraulic conductivity of 10^{-8} m s^{-1} was associated with impervious elements–Bonomi and Bellini (2003); Dassargues (1997). Drainage systems were integrated considering a seepage face with a Dirichlet BC, and pumping and reinjection wells were integrated by defining a Neumann BC.

Calibration

A calibration process in two steps was performed. In the first step, computed hydraulic heads were compared at 23 observation points with the mean hydraulic head value for 2012. The data observed for 2012 were chosen because it was the year when the information on underground constructions was the most exhaustive. According to Table 6, which shows historic piezometric data recorded at one observation point of the area studied between 1968 and 2015, 2012 appears to be a standard year in terms of piezometric levels. The aim of the calibration criterion of this first step was to provide a standard deviation of the hydraulic head smaller than 5 % of the difference between the highest and lowest heads across the area studied. The steady-state model can be calibrated on (1) material properties and (2) inflows parameters. Network losses are assumed uniformly distributed across the area

studied; recharge due to precipitation was based on computed data and was assumed to occur in the vegetated area; and clogging coefficients of rivers were based on literature data. As a consequence, hydraulic conductivities were locally adjusted to match the calibration criteria.

In the second step of calibration, the rate budgets computed from the drainage surface of the seven underground car parks of the area studied were compared with the dewatering rates declared by the infrastructure operator in 2012. The aim of the calibration step was to reproduce the infrastructure operation. It was possible to process this step because the drainage surfaces were defined by a Dirichlet BC. Conceptually, the algorithm removes water from the soil until reaching the BC. A rate budget analysis for each drainage surface gives this rate. The aim of the calibration criterion of this second step was to provide a standard deviation of the rate budget smaller than 5 % of the difference between the highest and lowest dewatering rate declared. In addition, the calibration criterion of the first step had to be maintained. The hydraulic conductivities of the molasse layer were locally adjusted to reach this criterion. The calibration results provided the first step criterion of 4.7 % and the second step criterion of 2 %. Figure 3 shows the results of the calibration process.

For the transient simulation, hydraulic heads were compared at two observation points, PZ 1 and PZ 2 (Fig. 1c), for the full simulation record. The first one, PZ 1, was chosen far from underground structures in order to be as little disturbed as possible. The second one, PZ 2, was chosen in the more densely built-up area. The comparisons between the computed and observed hydraulic heads are presented in Fig. 4.

Table 5 Boundary conditions for the actual state of groundwater flow

Boundary condition	Object	Zone	Value
Dirichlet BC	Inlet	Upstream surface	166–168 m asl
	Outlet	Drain: downstream line	Drain elevation: 152.2–158.3 m asl
Neumann BC	Drainage systems	Drainage surface of substructures	Drainage layer elevation
	Effective infiltration	Upper surface: vegetated areas	150 mm year ⁻¹
	Network losses	Upper surface	0–750 mm year ⁻¹
Cauchy BC	Pumping and reinjection wells	Pumping or reinjection point	Pumping rate
	River clogging	Bed of rivers	Hydraulic head 162–174.6 m asl In-out transfer rate 10^{-6} – 10^{-8} s^{-1}

Table 6 Historic mean values (by month) of piezometric data recorded from 1968 to 2015 at one observation point in the area studied

Month	January	February	March	April	May	June	July	August	September	October	November	December
Median for 1968–2015 [m asl]	163.55	163.45	163.45	163.33	163.40	163.45	163.37	163.17	163.07	163.17	163.37	163.37
Mean for 1968–2015 [m asl]	163.55	163.52	163.47	163.46	163.47	163.46	163.51	163.40	163.25	163.27	163.38	163.50
Standard deviation for 1968–2015 [m asl]	0.73	0.82	0.85	0.89	0.90	0.83	0.75	0.66	0.71	0.76	0.73	0.84
Mean for only 2012 [m asl]	163.69	163.30	163.05	163.28	163.40	163.48	163.33	163.00	162.99	163.14	163.37	163.84

Qualitatively, Fig. 4a shows that for PZ1, the computed hydraulic head is slightly overestimated and presents good dynamic behavior (i.e. slopes and amplitudes). Figure 4b shows that for PZ2, the computed hydraulic head seems out of phase. This can be explained by a deviation in the permeability estimation, and by the transient operation of underground structures (i.e. pumping wells and underground car parks) which were not taken into account in this study; however, the computed and observation mean values are very close. The computation is considered satisfactory due to the low piezometric amplitude.

Sensitivity analysis

A sensitivity analysis was performed to assess the influence of global hydraulic conductivity (i.e. Quaternary layers and Tertiary layer) and clogging coefficient variation on the computed hydraulic head. The multiplier factors tested ranged from 0.1 to 10. Tested parameters have been multiplied by each multiplier factor. The sensitivity of hydraulic conductivities of the Quaternary layers and Tertiary layer were tested separately. A total of 21 sensitivity simulations were run. For each sensitivity simulation, steady-state computed hydraulic head was compared with the mean value of observed hydraulic head in 2012. Residual values, δh , represented with box plots in Fig. 5, are equal to the difference between the computed values and the mean observed values.

To summarize, unlike clogging coefficient values, hydraulic conductivity (K) values were shown to be highly sensitive regarding the calibration of the flow model. The sensitivity

analysis highlights the opposing effect of the test range on the Quaternary layers' K values and the Tertiary layers' K values. This effect can be explain by the presence of pumping wells in the Quaternary layers and by the drainage layers of underground car parks near to the Tertiary layer:

- For Quaternary layers, when hydraulic conductivity was increased, the effect of pumping wells was reduced and residual values of hydraulic head increased. When hydraulic conductivity was decreased, the effect of pumping wells was increased and residual values of hydraulic head decreased.
- For Tertiary layers, when hydraulic conductivity was increased, the rate of drainage of the layer containing the underground car parks was increased because of the assigned Dirichlet BC (see 'Numerical representation of underground structures' section). Then, the computed hydraulic head decreased, the same as for residual values.

Results and discussion

Cumulative impact of underground structures on groundwater flow

Structure of flow systems

To assess the cumulative impact of underground structures on the structure of flow systems, flow streamlines from every

Fig. 3 Calibration results based on **a** observed hydraulic head and **b** observed rate budget from underground car parks with drainage systems. In both cases, the *dotted line* represents the axis where the computed value is equal to the observed value

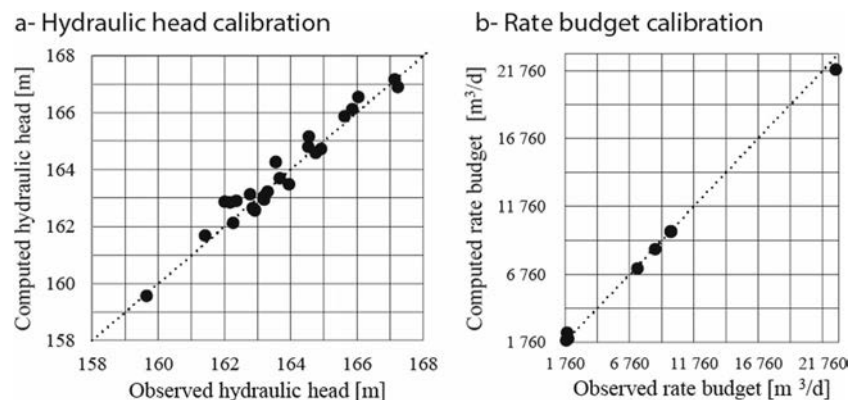
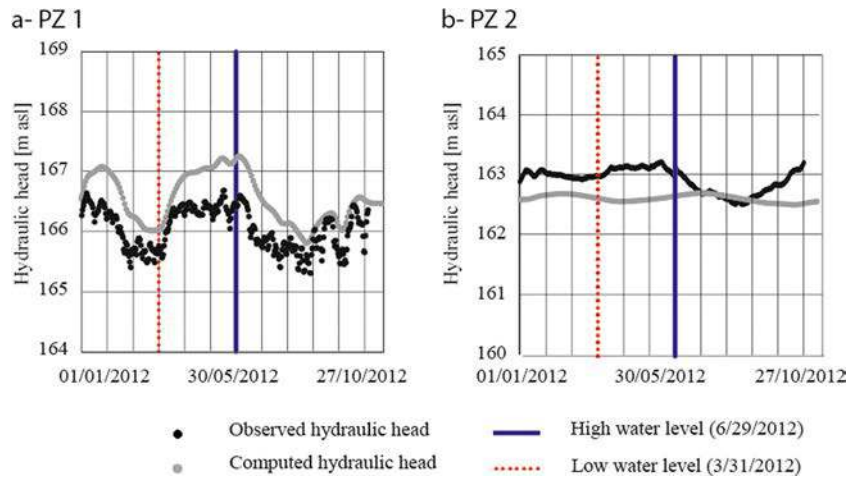


Fig. 4 Comparison between computed and observed hydraulic head during the simulation record of 2012 for observation points **a** PZ 1, and **b** PZ 2



outlet were monitored by particle tracking. Flow systems were distinguished according to starting points (glaciofluvial corridors, Rhone River) and the output points (Rhone River, pumping devices, drain) of flow streamlines determined with particle tracking.

For the potential state of the urban groundwater flow, three flow systems were distinguished (Fig. 6a and Table 7). S1' represents the streamlines from the south glaciofluvial corridor to the drain. S2' represents the streamlines from the north glaciofluvial corridor to the Rhone River. S3' represents the streamlines from the Rhone River to the drain.

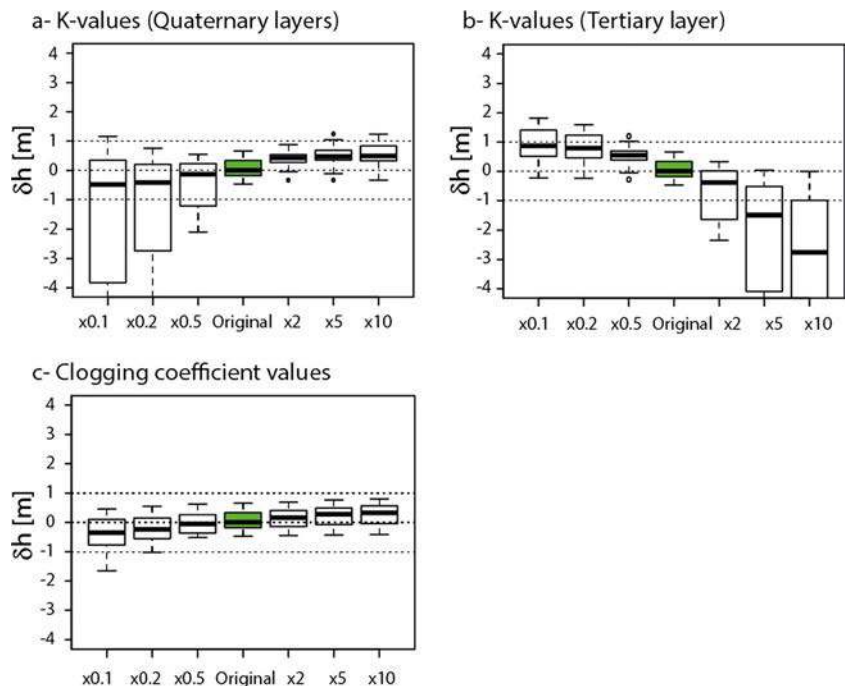
In the actual state of the urban groundwater flow, five flow systems were distinguished (Fig. 6b and Table 8)—S1 represents the streamlines from the south glaciofluvial corridor to the drain; S2 represents the streamlines from the Rhone River

to the drain; S3 represents the streamlines from the Rhone River to pumping devices (i.e. pumping wells and structures with a drainage system); S4 represents the streamlines from the north glaciofluvial corridor to pumping devices; and finally, S5 represents the streamlines from the north glaciofluvial corridor to the Rhone River.

The comparison between the actual state and the potential state of urban groundwater flow shows that the underground structures have fragmented the flow systems. In the potential state, three flow systems were established, whereas five were in the actual state; consequently, the urban groundwater regime has been modified.

The modification of the urban groundwater regime is well illustrated with the gradient inversion along the whole bed of the Rhone River (see flow system S3 in Fig. 6b). This

Fig. 5 Results of the sensitivity analysis illustrated by the residuals of the “best fit” model (green) and the various sensitivity scenarios for the calibrated parameters. All values represent the factors with which the parameters of the original “best fit” models were multiplied. The *box plots* show the median (horizontal line within the box), the quartiles Q1 and Q3, the upper and lower whiskers (horizontal bars outside of the box), as well as extreme outliers beyond the whiskers. *K*-values for **a** Quaternary and **b** Tertiary layers. **c** Clogging coefficient values



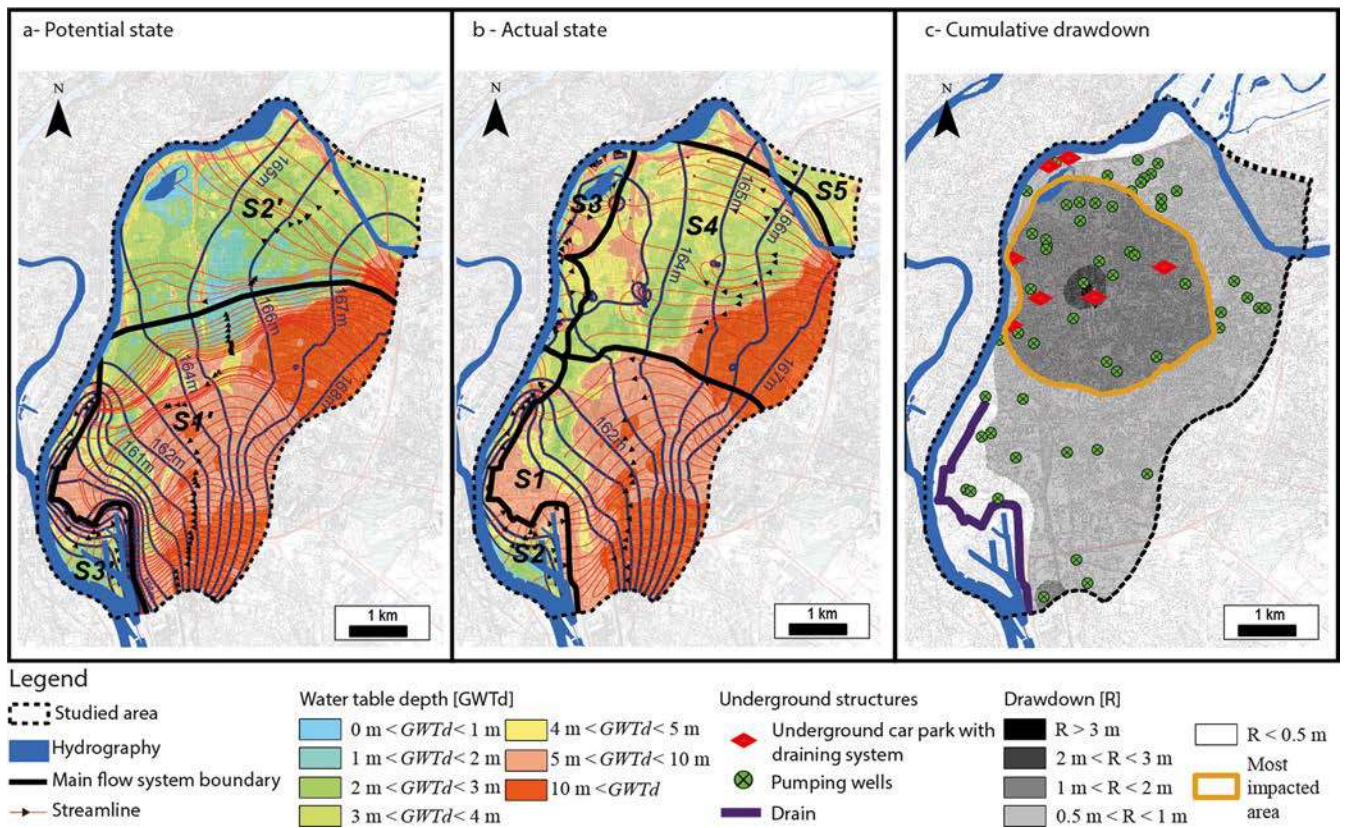


Fig. 6 Structure of the main flow systems ($S1'$, $S2'$, $S3'$, and $S1$ – $S5$) and water-table depth (GWTD), in **a** potential and **b** actual states. **c** Cumulative impact of underground structures on the water-table elevation

phenomenon is observed at a maximum distance of 1 km from the Rhone River. Quantitatively speaking, in flow system S3 of the actual state, the Rhone River contributes preponderantly to groundwater recharge (i.e. $2.21 \times 10^4 \text{ m}^3 \text{ d}^{-1}$ in Table 7). In the potential state, this urban area was shown to be preponderantly recharged by the glaciofluvial corridor. This modification of the groundwater flow regime could lead to groundwater quality problems in the case of Rhone River contamination.

According to Attard et al. (2016), the quantification of flow systems is crucial for managing groundwater resources in an urban area. It allows for the characterization of local aquifer productivity in terms of water supply for industrial and domestic uses. The computation of inflows in the flow system area provides an initial indicator for the installation of pumping devices (i.e. pumping wells, structures with drainage systems). It can be assumed that if the rate of a device is non negligible (i.e. with several orders of magnitude) with respect to flow-system inflows, then the overall structure of the urban flow system can be disturbed.

In addition, the quantification of flow systems allows for determination of the quantitative origin of groundwater (e.g. direct recharge, recharge from river). This

information provides a second indicator in terms of groundwater quality and temperature. Regarding the geothermal exploitation of an urban aquifer, García-Gil et al. (2014) showed the thermal impact of river-water recharge and highlighted a cooling effect during winter-spring floods. In the case of the present work, it can be assumed that the modification of the urban groundwater regime generated by underground structures (i.e. flow system S3 of the actual state) can increase the thermal impact and disturb the geothermal devices of flow system S3. Regarding groundwater quality, Jurado et al. (2014) showed that high concentrations of pollutants can be found when an aquifer is infiltrated by a polluted river. For flow system S3, which was shown to be infiltration by the Rhone River, it can be assumed that the cumulative effect of underground structures on groundwater could favor contamination subsequent to accidental pollution upstream of the city.

Water-table elevation

Figure 6a,b shows water-table depth (GWTD) in the potential state and in the actual state. Figure 6c shows the difference of

Table 7 Characteristics of flow systems in the potential state of groundwater flow

Flow system	Main inlet	Main outlet	Inflow from glaciofluvial corridor ($\text{m}^3 \text{d}^{-1}$)	Inflow from direct recharge ($\text{m}^3 \text{d}^{-1}$)	Inflow from network losses ($\text{m}^3 \text{d}^{-1}$)	Inflow from Rhône River ($\text{m}^3 \text{d}^{-1}$)	Underground structures
S1'	Glaciofluvial corridor	Rhone River	1.18×10^5	1.52×10^3	2.13×10^4	–	None
S2'	Glaciofluvial corridor	Drain	6.21×10^3	2.49×10^3	1.31×10^4	1.14×10^3	Drain
S3'	Rhone River	Drain	–	1.77×10^2	2.26×10^3	2.30×10^5	Drain

water-table elevation between the potential state and the actual state of groundwater flow. A global drawdown can be seen between these two states: the water-table elevation is considered disturbed in 82 % of the area studied (i.e. zone where drawdown is higher than 0.5 m). The drawdown reaches more than 3 m (see black spots in Fig. 5c). The most impacted area with a drawdown higher than 1 m is identified. This zone includes five underground car parks with drainage systems and 22 pumping wells which contribute to the drawdown. A non-impacted zone is identified in the south of the area studied. It can be explained by the same Dirichlet boundary condition imposed at the drain location.

Figure 6a shows extended areas in the potential state where GWTd is less than 2 m. A military map dating from 1820 to 1866 (MEDDE 2015) showed several wetlands in the area (Fig. 7). This is the most representative period of a potential state regarding the definition provided in this paper (i.e. no

underground structures). Not all wetlands can be superimposed over computed low GWTd zones. In fact, the topography has been modified (e.g. embankments, urban railways). In addition, in the 19th century, the city's drains had not yet been built. In the actual definition of the potential groundwater flow, this drain was maintained so as not to disturb the main regime of the groundwater outlet.

The representation of the cumulative impact of underground structures on the water-table elevation should not overshadow the head-rise effect of several underground structures. In fact, the comparison between the actual and the potential state of water-table elevation shows that the barrier effect, which is known to generate head rise upstream of impervious structures (Ricci et al. 2007; Pujades et al. 2012; Deveughèle et al. 2010; Bonomi and Bellini 2003; Marinos and Kavvadas 1997; Dassargues 1997; Merrick and Jewell 2003; Epting et al. 2008) is fully compensated by pumping

Table 8 Characteristics of flow systems in the actual state of groundwater flow

Flow system	Main inlet	Main outlet	Inflow from glaciofluvial corridor ($\text{m}^3 \text{d}^{-1}$)	Inflow from direct recharge ($\text{m}^3 \text{d}^{-1}$)	Inflow from network losses ($\text{m}^3 \text{d}^{-1}$)	Inflow from Rhône River ($\text{m}^3 \text{d}^{-1}$)	Underground structures
S1	Glaciofluvial corridor	Drain	1.13×10^5	9.64×10^2	1.43×10^4	–	- 15 pumping wells - 4 structures with deep foundations - 6 km of subway lines - Drain
S2	Rhone River	Drain	–	1.99×10^2	2.60×10^3	2.33×10^5	- 2 structures with deep foundations - Drain
S3	Rhone River	Pumping wells and drainage systems	–	6.77×10^2	1.67×10^3	2.21×10^4	- 7 pumping wells - 4 structures with deep foundations - 1 km of subway lines - 4 underground car parks
S4	Glaciofluvial corridor	Pumping wells and drainage systems	1.14×10^4	1.48×10^3	1.96×10^3	–	- 33 pumping wells - 36 structures with deep foundations - 1 km of subway lines - 3 underground car parks
S5	Glaciofluvial corridor	Rhone River	1.52×10^3	3.82×10^2	1.88×10^3	–	None

devices. In addition, the cumulative representation of the impact hides the local head rise effect of reinjection devices equipping several underground car parks. This effect would be shown with the computation of a scenario focusing on the construction of an underground structure of this type.

In many cases, there are indirect issues related to the evolution of piezometric depressions. This phenomenon can give rise to compactions (NSREA 1995; Yoo et al. 2009, 2012; Modoni et al. 2013) or contribute to a change of groundwater quality (Chae et al. 2008). In this paper, another issue deserves attention: the underground of Lyon has been developed ever since the beginning of groundwater exploitation (i.e. subway lines, underground floors), without taking into account the potential elevation of the water table. This potential state could be reached in the case of a global shutdown of pumping devices—i.e. black-out scenario for which Bo et al. (2015) proposed a review and analysis of previous urban blackouts across the world. In that

case, considering that the water-table depth is less than 3 m (Fig. 5a) in 28 % of the area studied, it seems probable that a large number of underground floors will be flooded.

Role played by different underground structures

Impervious structures

The simulation of the actual state of groundwater flow was compared with an intermediate state. In the latter, all the impervious structures were removed from the model. All the pumping devices of properties (i.e. car parks with drainage systems, pumping wells) remained unchanged. The result of the simulation showed no significant change in groundwater flow (i.e. water-table elevation and structure of flow systems). In fact, the differences observed between the actual and the intermediate water-table elevation—less than 5 cm—were in

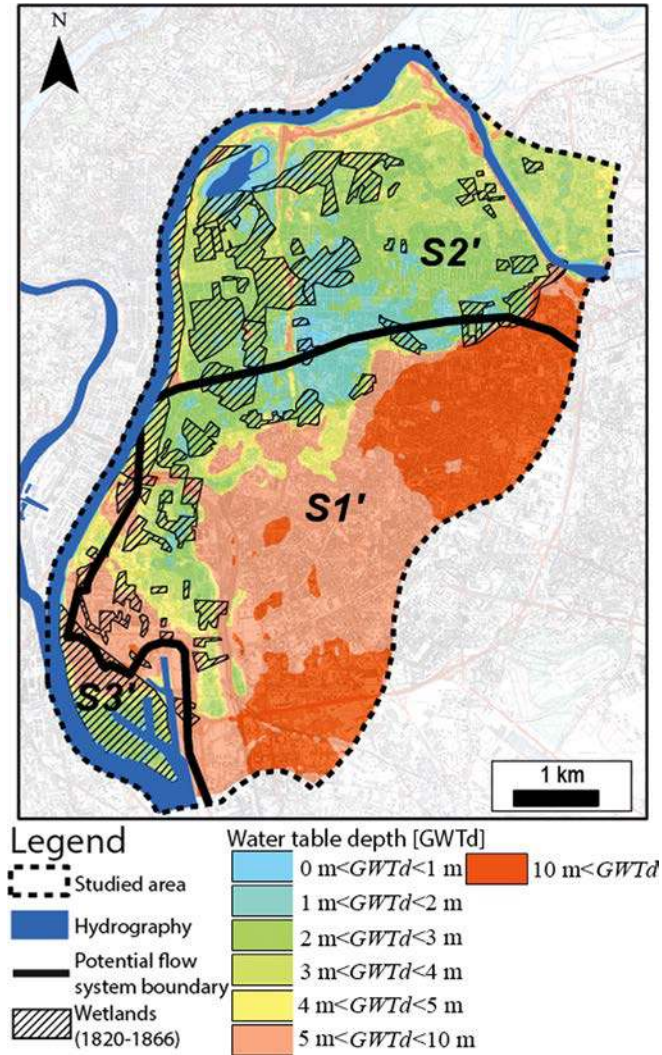


Fig. 7 Superimposition of computed water-table depth and historically known wetlands (from military maps 1820–1866, MEDDE 2015). Flow systems are depicted in the potential state

the order of magnitude of the numerical error tolerance fixed at 1 % and did not allow identifying a barrier effect caused by impervious structures.

This non-impact can be explained by the small hydraulic gradient of the area studied. According to Font-Capo et al. (2015), the impact caused by impervious structures may not be perceptible if the hydraulic gradient is small (i.e. close to 0.1 %). According to Fig. 8, which represents the hydraulic gradient in the actual state of the groundwater flow, all the impervious structures are built in areas where the hydraulic gradient is lower than 0.5 %.

Underground car parks with drainage and reinjection systems

Due to the non-impact of impervious structures observed in the previous section at the scale of the structure area and at the scale of the overall area studied, it

can be concluded that pumping devices have a preponderate effect on the urban groundwater flow. Obviously, the higher the pumping rate, the bigger the impact. Therefore, regarding the flows involved, underground structures built with a drainage and reinjection system deserve special attention. For example, Fig. 9 focuses on the urban flow in the location of the biggest underground car park of the area studied. This underground car park has seven underground floors with a capacity of 1,800 vehicles. The drainage system of the structure involves $22,800 \text{ m}^3 \text{ d}^{-1}$. The water is reinjected nearby, upstream of the structure, by 13 reinjection wells. According to Table 7, this pumping rate is higher than the inflow of the overall flow system, i.e. $14,000 \text{ m}^3 \text{ d}^{-1}$. The comparison between these rates shows how the underground car park could modify the natural structure of urban flow systems. Figure 9 shows the

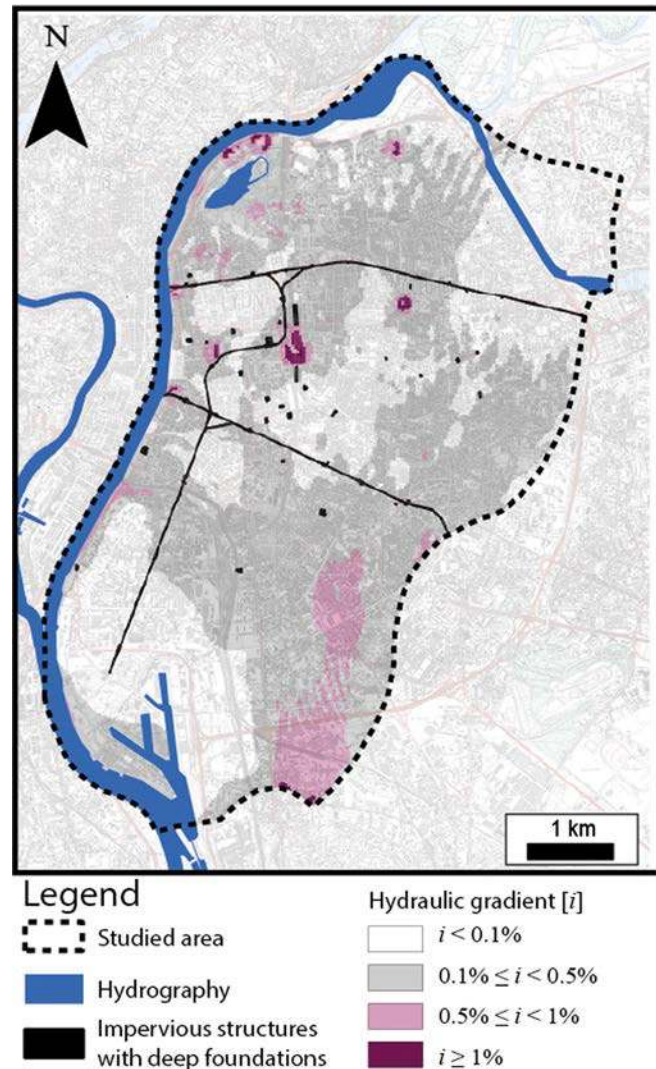


Fig. 8 Hydraulic gradient i in the actual state of groundwater flow

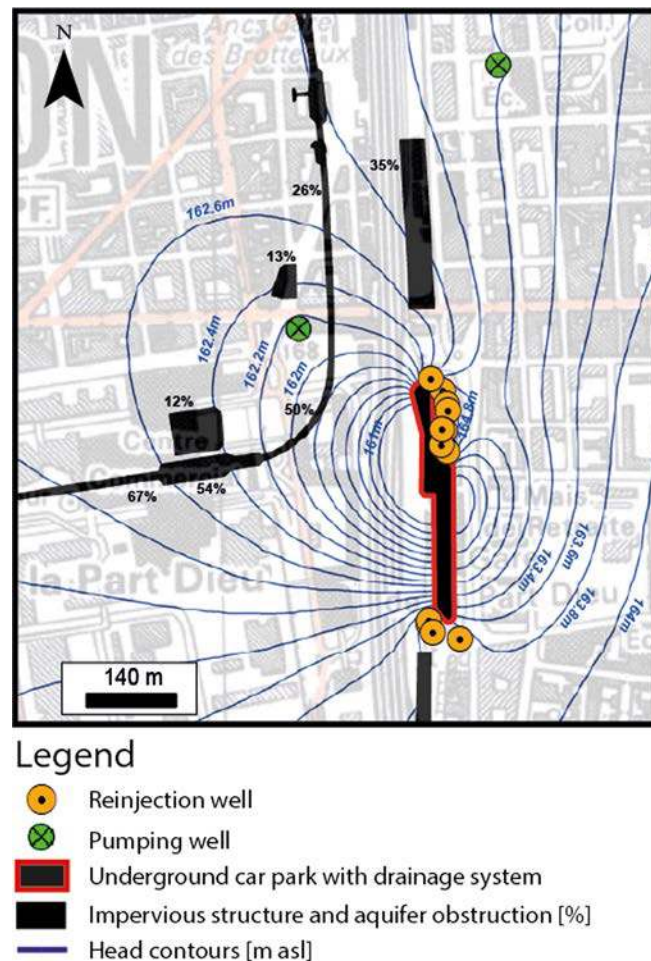


Fig. 9 Local groundwater flow around an underground car park of the area of La Part-Dieu district

structure's area of influence, more than 100 m upstream and downstream. Figure 9 also shows the barrier effect of the underground car park with respect to the natural east–west flow.

Temporal stability of flow systems

To assess the temporal stability of the flow systems, the area of instability was defined as the zone where the boundary between 2 flow systems can move. The transient simulation showed the high temporal stability of the flow systems: 9.3 % of the area studied was considered unstable. The structure of the flow systems of the area studied was compared under high and low water conditions (see Fig. 10). In addition, the stability of the flow systems was demonstrated by comparison between the transient systems and the steady systems.

The temporal stability of flow systems is a key point regarding groundwater management. In fact, if flow systems are demonstrated to be stable at a decision-making scale, the depiction of steady-state flow systems becomes a relevant method for proposing regulated zoning for underground construction and groundwater exploitation. This approach could complement the 3D planning process proposed by Li et al. 2013a and Li et al. 2013b. This 3D planning consists of a vertical depiction of the potential in urban underground resources: groundwater, geothermal energy, geomaterials and space. Stable urban flow systems and their characteristics (e.g. inflows, outflows, sources of pollution) should be superimposed with the potential zoning of underground space in order to prevent risks and disturbances inherent to urban underground development (e.g. degradation of water supply quality, interferences between pumping wells or between geothermal devices).

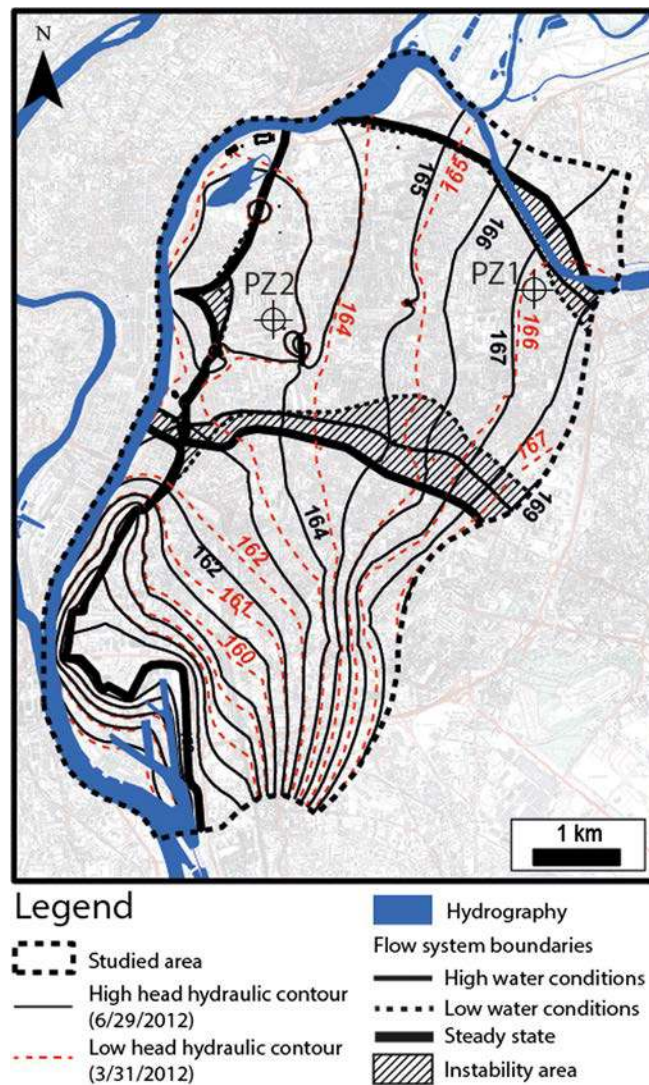


Fig. 10 Representation of head contours in high and low water conditions. Delineation of the main flow system boundaries in high/low water conditions and in steady state

Summary and conclusions

The aim of this work was to quantify the cumulative impact of underground structures on urban groundwater flow. A three dimensional modeling approach was used at the scale of the city of Lyon (France). Several simulations were run: (1) the actual state of urban groundwater flow (i.e. with all known underground structures); (2) the potential state of urban groundwater flow (i.e. without underground structures); (3) an intermediate state (i.e. without impervious structures); and (4) a transient simulation of the actual state of groundwater flow. The numerical representation of underground structures was shown to be efficient for quantitatively depicting urban flow systems and defining a potential state of urban

groundwater. Flow systems were distinguished according to the main input and output of flow streamlines. The following conclusions may be drawn from this study:

1. Underground structures involving pumping/reinjection rates caused a fragmentation of urban flow systems. Consequently, the urban groundwater regime had been modified and an inversion of the interaction between the groundwater and the river was observed. This regime modification can lead to an influx of polluted water from the river to the groundwater.
2. Regarding water-table elevation, the cumulative effect of underground structures was a global drawdown. This drawdown was caused by pumping devices (i.e. pumping

wells and structures with drainage systems). Due to the strong dependence of the actual water-table elevation on pumping devices, the potential state of water-table elevation (i.e. water-table elevation in case of no pumping device operation) should be taken into account when building new structures. The stoppage of several pumping devices could lead to the flooding of underground floors.

3. Because of the small hydraulic gradient of the area studied, the impact of impervious structures was negligible. On the other hand, the influence of structures with drainage systems was emphasized. These underground structures have a major influence on urban flow systems.
4. Transient simulation demonstrated the temporal stability of flow system structure for this case. Thus, the relevance of the steady state approach for the quantitative depiction of flow systems was demonstrated. The stability of flow systems was considered an asset regarding underground planning.

According to the main results presented in this paper, several recommendations and perspectives can be proposed regarding urban underground planning:

- For each urban area with high potential for urban underground development, groundwater flow systems should be depicted quantitatively and their stability should be considered as a major issue. The main underground structures must be taken into account to quantify these flow systems.
- Considering that the stability of flow systems is an issue, regulated zoning should allow or prohibit the building of new pumping devices as a function of the total inflow of the flow system. If the pumping rate of a structure is of the same order of magnitude as the total inflow of the flow system, the construction should not be permitted.
- Considering the choice of design techniques and regarding the influence of the flow system, the drainage system should be considered as having a greater impact than an impervious structure.
- As the depiction of flow systems allows for the determination of the quantitative and qualitative origin of the groundwater, the area of the flow system should be used to establish zoning regulation regarding water supply.
- Finally, the accurate quantitative depiction of urban flow systems should help to understand the fate of urban pollutants (e.g. industrial wasteland).

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