A hydrogeological conceptual approach to study urban groundwater flow in Bucharest city, Romania

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Abstract Management of groundwater systems in urban areas is necessary and can be reliably performed by means of mathematical modeling combined with geospatial analysis. A conceptual approach for the study of urban hydrogeological systems is presented. The proposed approach is based on the features of Bucharest city (Romania) and can be adapted to other urban areas showing similar characteristics. It takes into account the interaction between groundwater and significant urban infrastructure elements that can be encountered in modern cities such as subway tunnels and water-supply networks, and gives special attention to the sewer system. In this respect, an adaptation of the leakage factor approach is proposed, which uses a sewer-system zoning function related to the conduits' location in the aquifer system and a sewer-conduits classification function related to their structural and/or hydraulic properties. The approach was used to elaborate a single-layered steady state groundwater flow model for a pilot zone of Bucharest city.

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Introduction

Groundwater, representing about 30.1 % of Earth's freshwater (Shiklomanov 1993), is the most important available water resource. Nowadays, it is widely accepted that climate change and human activities threaten this resource. The magnitude of these threats is particularly accentuated in urban areas. This is due to the continuous horizontal and vertical expansion of modern cities. Such extensions have been demonstrated to affect groundwater systems quantitatively and qualitatively. As a direct consequence of urban land-use change, the natural hydrological cycle is disrupted and recharge of the aquifer system is considerably modified, which is mainly due to the continuous decreasing contribution of percolation from rainfall and of the increasing water inputs coming from different urban sources such as the leakage from the water supply network (WSN; e.g. Vázquez-Suné and Sanchez-Vila 1999; Martinez et al. 2010) and from the sewer system (SS; e.g. Vázquez-Suné and Sanchez-Vila 1999; Rueedi et al. 2009). On the other hand, an unnatural increase or decrease of the groundwater level due to the introduction, modification, or elimination of different urban water-cycle components, can disturb a given flow state (e.g. Vázquez-Suné and Sanchez-Vila 1999; Al-Rashed and Sherif 2001). The rise of the water table can lead to flooding of underground structures, to increased groundwater infiltration into sewers, and to augmented development costs of infrastructure works (associated with operations like dewatering, draining or waterproofing). From a qualitative perspective, important contributions of groundwater recharge related to SS losses (such as those reported by Rueedi et al. 2009, Wolf et al. 2006 and Martinez et al. 2010) reflect a high groundwater contamination potential. In coastal cities, groundwater quality can

also be affected by seawater intrusion that can be induced by a decrease of the groundwater level, usually associated with excessive groundwater abstraction (e.g. Vázquez-Suné and Sanchez-Vila 1999; Nakayama et al. 2007).

In Bucharest, Romania, several problems related to groundwater flow disturbance emerged with the first subway line development (1976–1981) and the NW–SE parallel lining projects (1976–1980) of the Dâmbovița River (Fig. 1) which flows through the city. These public works created a groundwater flow barrier and drastically reduced the natural groundwater discharge to the river. In order to reduce these effects, two horizontal drains located on both sides of the Dâmbovița River were built (see Fig. 2); however, the first 10-km segment of the right-side drain broke down leading to a local increase of the groundwater in the right bank of the river. Currently, the city water operator estimates that the left-side drain discharges groundwater at approximately 0.88 m^3/s. The water operator also registered significant groundwater infiltration into the SS (about 1.88 m^3/s during 2013); while on the other hand, losses from the WSN (total technical losses estimated to be about 2.4 m^3/s during 2013) represent an important groundwater recharge source.

The objective of this research is to develop an approach that will help in understanding and assessing the interaction between groundwater and urban infrastructure in the city of Bucharest with a focus on the sewer system. This will support future developments of integrated urban groundwater management practices in Bucharest. The study illustrates a selected example, focusing on the anthropogenic impacts that are associated with important changes to groundwater flow, recharge and discharge.

Pilot zone characteristics

As a demonstration of the proposed conceptual approach to study groundwater flow in Bucharest, a pilot zone in the western part of the city (downstream Lake Lacul Morii) was chosen. This urban zone covers an area of about 9 km^2 (Fig. 1) and is considered to be relevant for the development of the Bucharest groundwater conceptual model because it includes the most important hydrological components of the city (detailed in the following).

The pilot area is a buffer zone for the lined Dâmbovița River. In the south east, the study area is delineated by the future subway line. Currently, hydrogeological and geotechnical investigations are executed in the region as part of the tunnel design activity. The southern part of the pilot zone includes part of a residential area (Cotroceni) where basement flooding and derived structural problems have been observed due to the rise of the groundwater level after the Dâmbovița River lining works were completed.

The path of the Dâmbovița River in the study section is completely artificial. Before this river was lined, the riverbed naturally drained the groundwater of the central Bucharest area. The project associated with the lining of the river involved setting up a large sewer collector consisting of two main wastewater conduits (Fig. 2) as well as a gallery with the role of draining the groundwater of the shallow aquifer. Unfortunately, the drainage gallery does not function in a large segment of the city centre
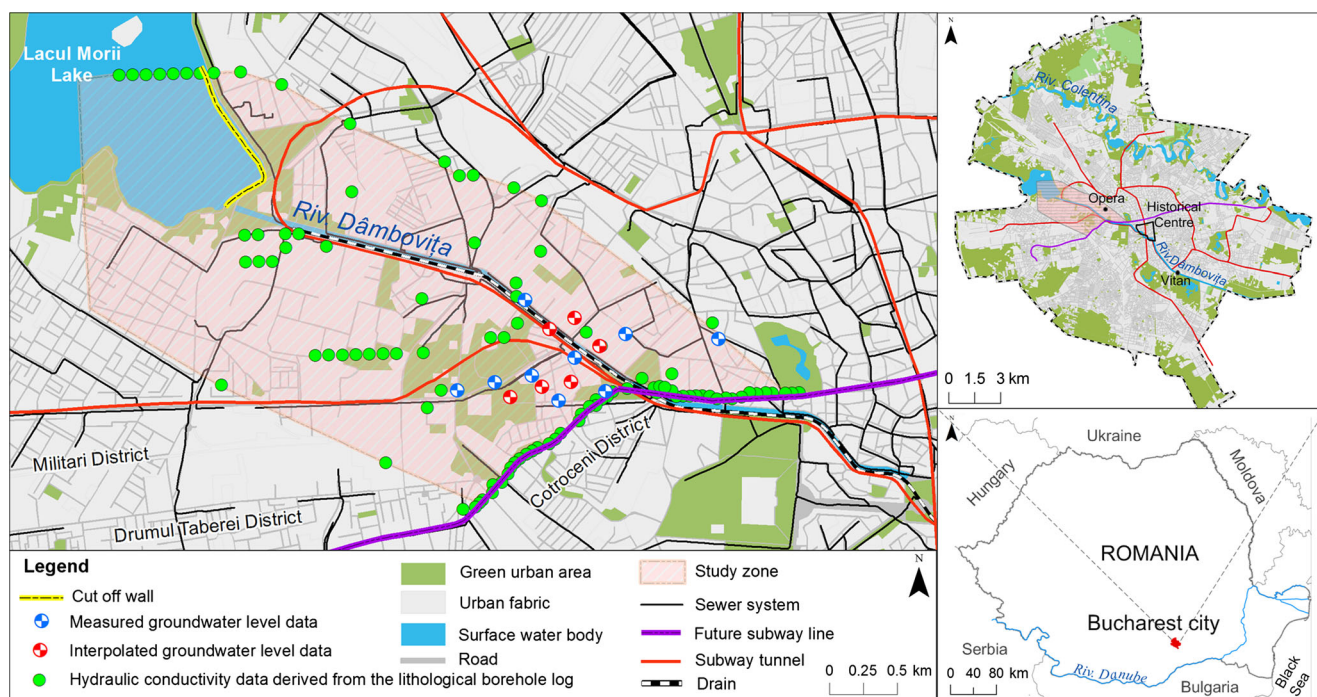

Fig. 1 Study zone: location, land-use and spatial distribution of the used data
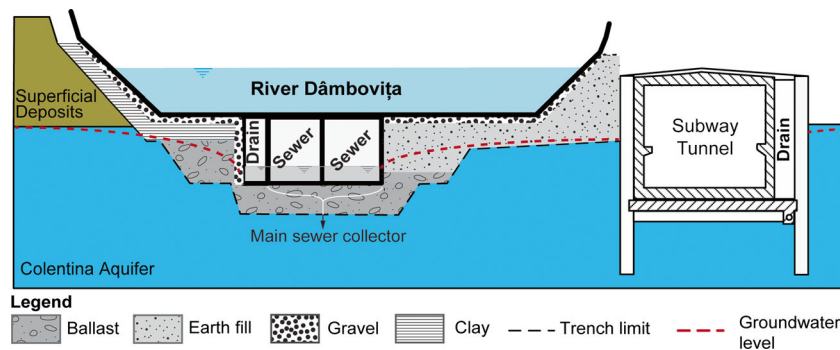
Fig. 2 Generic cross section perpendicular to the main sewer collector

(Opera - Vitan), a situation which led to rising of the groundwater level, triggering further flooding of underground structures.

The Lacul Morii artificial lake supplies the Dâmbovița River and is located in the north-eastern part of the study zone, about 6 km from the city center. Its main purpose is to protect Bucharest against floods. It was developed by constructing a dam composed of a central body of concrete (15 m high) and two earth dykes with extensions of 6 km length. With a surface area of about 2.5 km^2, it is the largest lake of the city. The volume of the lake is about 14.7 million m^3 and it has an additional capacity of 1.6 million m^3 to collect floodwater. The lake regulates the constraint water sanitary flow rate on Dâmbovița River. In order to impede seepage, a bentonite cut-off wall of about 23 m depth and a thickness of 0.6 m has been built under the central body of the dam and under the northern dyke (Popescu and Lăzărescu 1988).

The pilot zone includes three segments of subway tunnels (Fig. 1). Two of them are perpendicular to the groundwater general flow direction of the area and the longest one is parallel to the lined river. The subway tunnels belonging to this last segment were built by cut and fill, and the others were made using tunneling boring machines. The analyzed zone includes several natural green areas acting as natural recharge elements for the aquifer system, which constitute 32 % of the surface area in the pilot zone. The rest is covered by concrete and asphalt (streets, squares, and others).

Conceptual approach

The main elements of the urban hydrologic cycle of Bucharest are: the aquifer system, the water supply network, the sewer system, a drain conduit constructed along the main sewer collector, the subway tunnels, the groundwater recharge from precipitations, the groundwater exchanges with the natural and with the artificial lakes, as well as its exchanges with the Colentina River and with the lined Dâmbovița River. A schematic image of the main contributory elements of the Bucharest urban groundwater is illustrated by Fig. 3. The conceptual approach used for the groundwater flow analysis of the pilot zone of Bucharest is described in the following and illustrated by Fig. 4.

Conceptual components

The aquifer system structure

According to Liteanu (1952), the city of Bucharest lies on a Quaternary sedimentary aquifer system composed of three main aquifer units (referred to as Frătești strata, Mostiștea and Colentina in Fig. 5). The uppermost aquifer unit, Colentina, is an unconfined aquifer comprised primarily of sands and gravel. This aquifer has a direct interaction with most of Bucharest's infrastructure elements. Between Mostiștea and Colentina lies a clayey aquitard called "Intermediary Deposits". Natural hydraulic
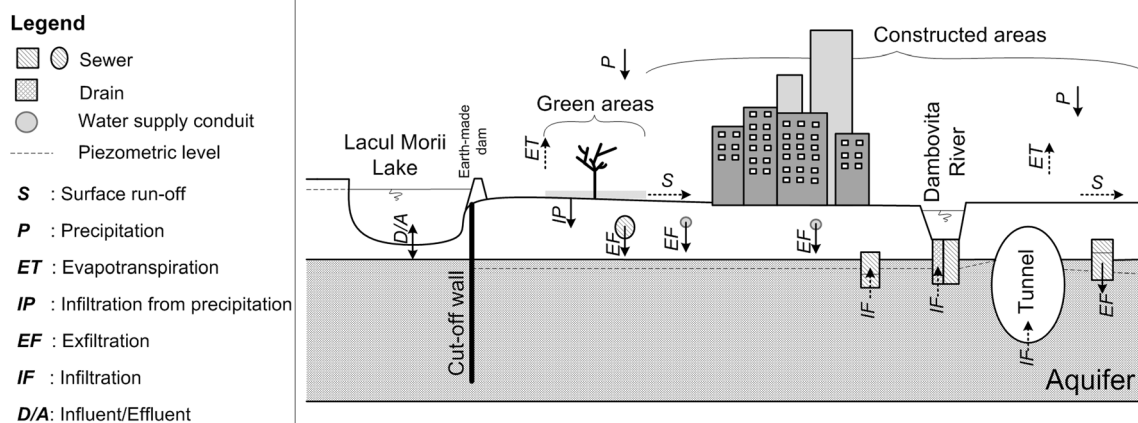

Fig. 3 Main elements of the urban hydrologic cycle of the city of Bucharest

connections exist between the two upper aquifer units Colentina and Mostistea, which have been revealed by the 3D geological model of the Bucharest region (elaborated by Serpescu et al. 2013) and correspond to the zones where the Intermediary Deposits aquitard pinch out; however, such connections do not occur within the study zone.

A one-layer groundwater flow model has been used to study the interaction between the aquifer (reduced to the aquifer unit called Colentina) and the existing urban infrastructure. The aquifer structure has been delineated using the geological model elaborated by means of geographical information system (GIS)-based three-dimensional (3D) geological tools (Gogu et al. 2011). This model consists of 8 geological cross sections interpreted using litho-stratigraphical correlation of 73

borehole logs. Figure 6 illustrates the elaborated cross sections of the 3D geological model.

The sewer network

Taking into account the hydraulic gradient between the wastewater pipes and the groundwater level (Fig. 7), distinct sewer segments can act as a recharge source for groundwater or act as a drain for the aquifer. It is likely that both cases can be found in the area. A summary of existing models that can be used for the assessment of the interaction between groundwater and sewer systems is given in the electronic supplementary material (ESM). For the present study, the estimation of such interaction is
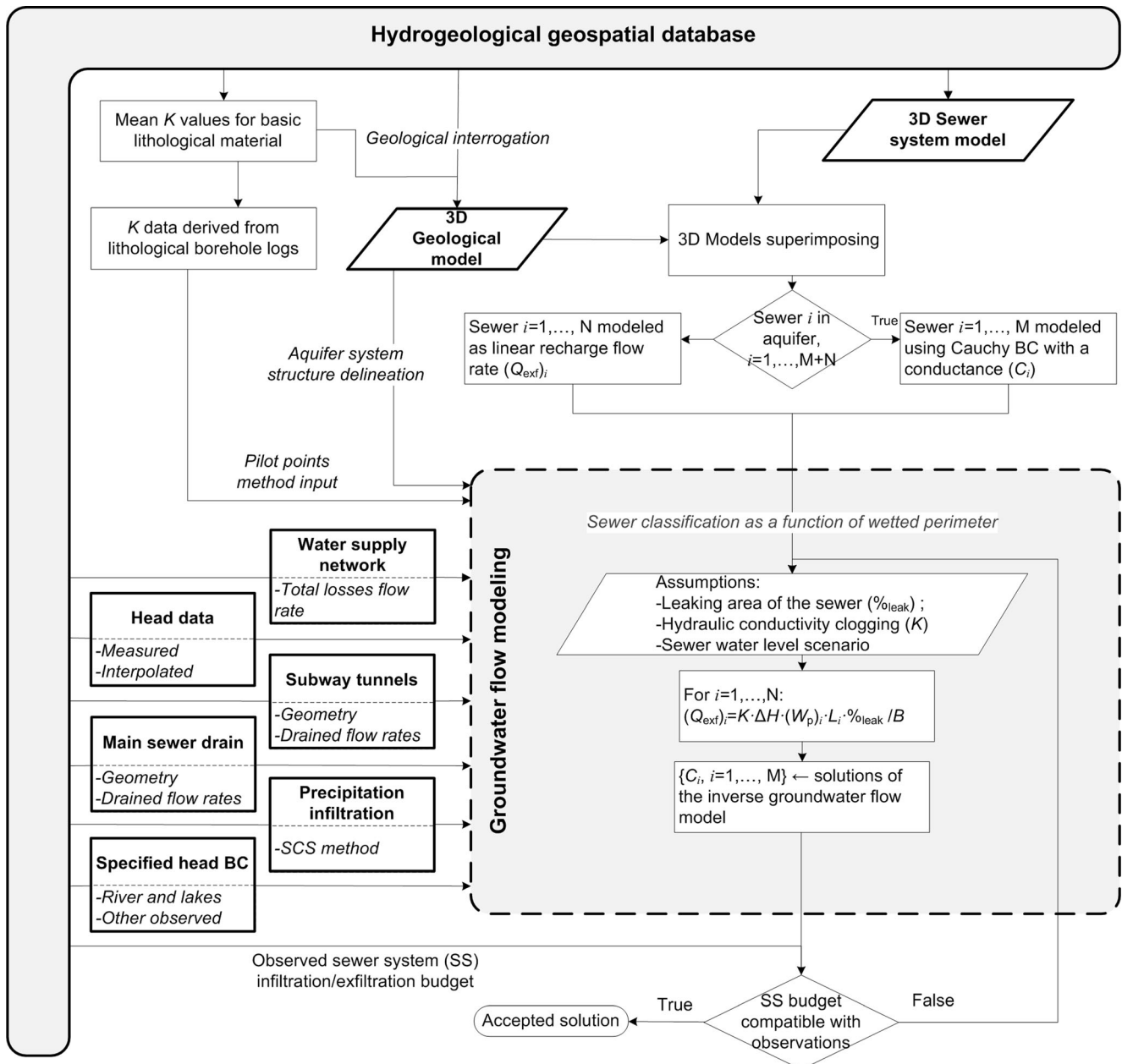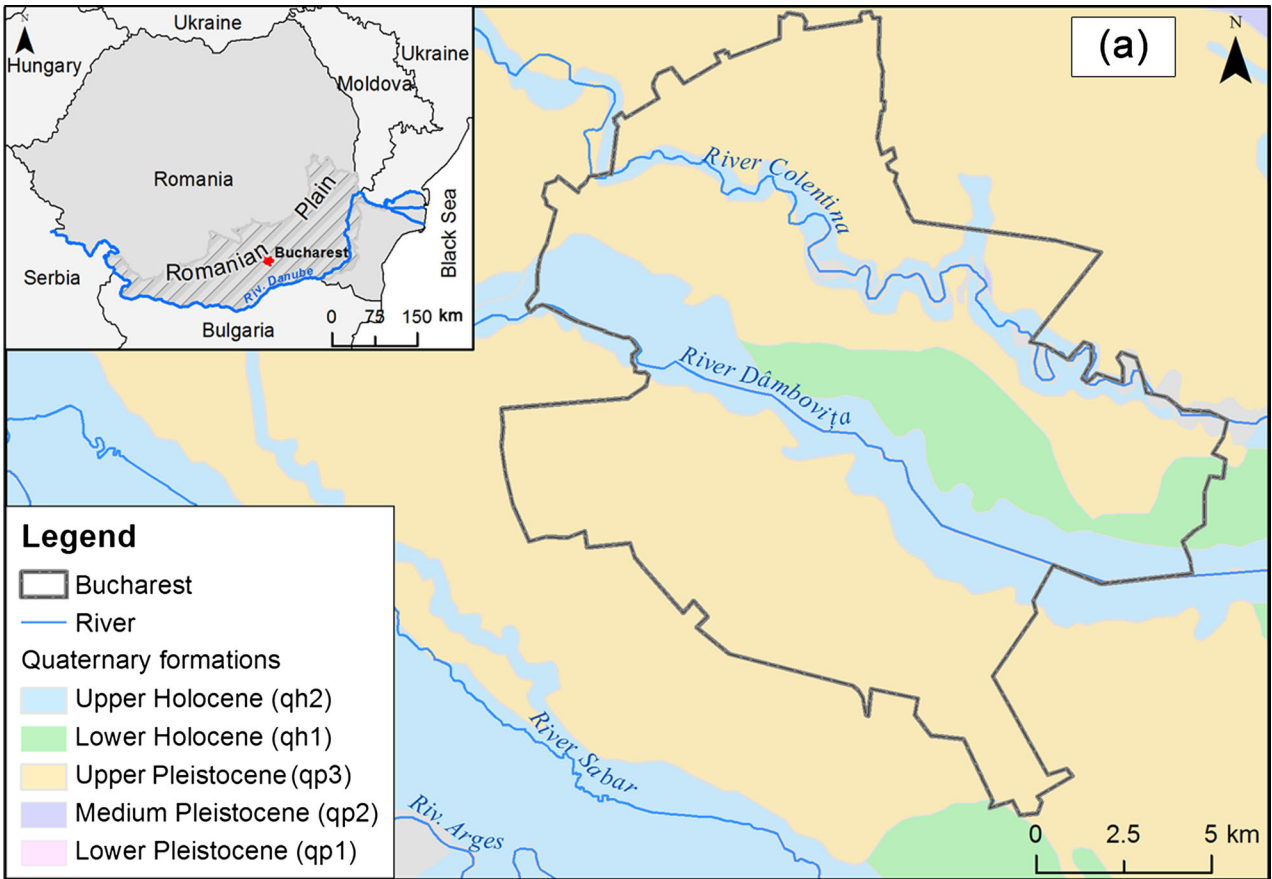

Fig. 4 Conceptual scheme for the urban groundwater flow model in the pilot zone of Bucharest. *BC* boundary condition

Age			Depth (m)	Thickness (m)	Lithology	Hydrogeological units	
Period	Epoch						
QUATERNARY	Holo-cene	$qh2$	0-15	5-10	Loess, clay		Superficial deposits
		$qh1$					
	Pleistocene	qp_3^3	4-25	5-25	Gravels & sands		Colentina
		qp_3^2	15-30	5-10	Clay		Intermediary deposits
		qp_3^1	20-50	10-20	Sand		Mostiștea
		qp_2	45-100	20-120	Marl, clay, silt with sand intercalations		Coconi strata
NEOGENE	Pliocene	qp_1 - ro	70-280	15-115	Gravels & sands with clayey intercalations		Frătești

Fig. 5 Geological setting of the city of Bucharest: **a** geological map, **b** stratigraphic column of Bucharest
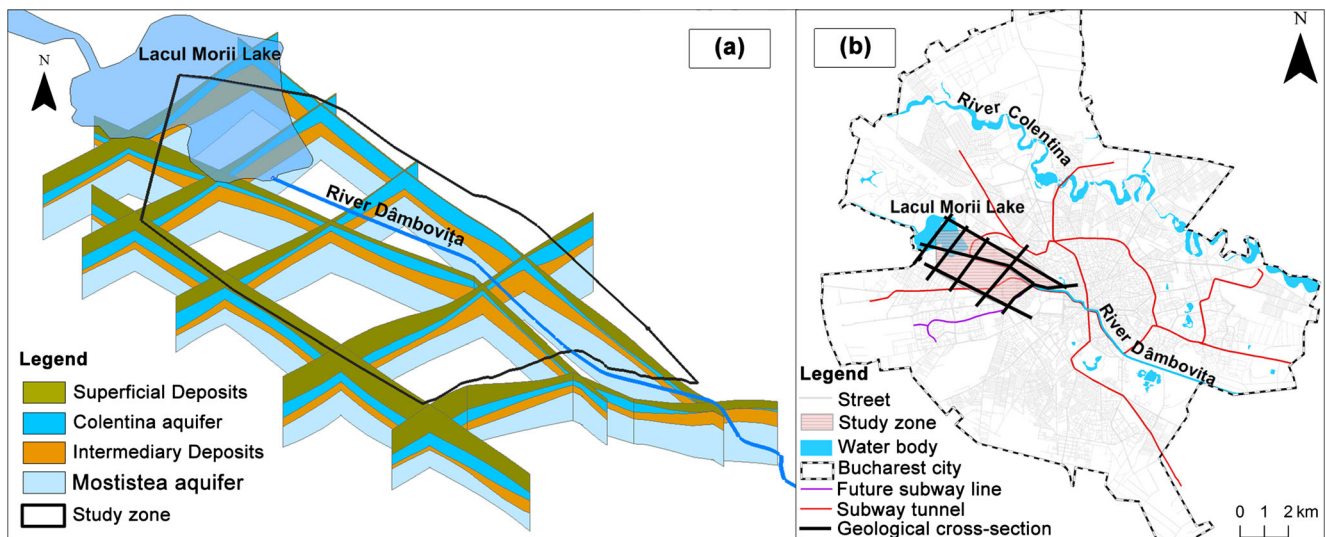
Fig. 6 **a** Geological cross sections and **b** their locations in the study zone

done using the leakage factor approach (Gustafsson 2000; Rauch and Stegner 1994). The assessment is based on the following simplifications:

– All sewers might have defects
– Uniform distribution of defects along each sewer
– Defect area is proportional to sewer's wetted perimeter
– Sewers in the Superficial Deposits are subjected to exfiltrations
– Sewers partially or totally in the aquifer unit Colentina can exhibit infiltration or exfiltration

The first step toward assessing the interaction between the sewer system and groundwater consists of identifying the position of each sewer in the aquifer system (see Fig. 8). This requires the use of 3D geometry for both systems (aquifer system and SS) and will allow for predefining each sewer's behavior as either (1) the possibility of exfiltration only for the sewer positioned above the aquifer unit or (2) the possibility of infiltration or exfiltration for sewers intersecting the aquifer unit. Thus, modeling the sewer exchange with groundwater is done by classifying the sewer system into two zones as described in the following.
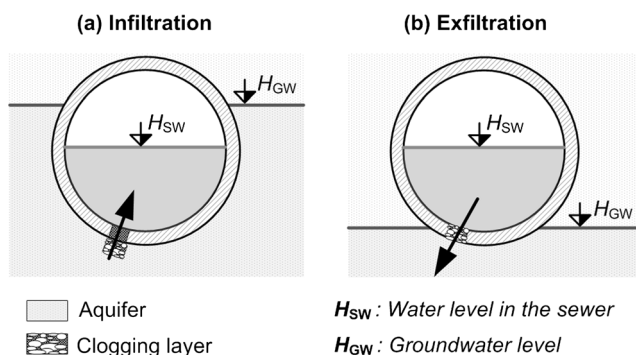

Fig. 7 Typical schematization of possible interactions between groundwater and a defected sewer: **a** groundwater infiltration into a sewer, **b** sewage exfiltration into groundwater

Zone 1: sewers located above the aquifer unit (sewers in the Superficial Deposits). These sewers are supposed to exhibit leakage behavior only, thus they are modeled using linear recharge rates. The recharge rates are calculated using:

$$Q_{\mathrm{ex\,f}} = K \cdot \frac{\Delta H}{B} \cdot (W_{\mathrm{p}} \cdot L) \cdot \%_{\mathrm{leaks}} \qquad (1)$$

where Q_{exf} [m^3/day] is the total exfiltration rate of the considered sewer segment having a length L [m] and a wetted perimeter W_{p} [m] generated with the water level in the sewer for the analyzed scenario, B [m] is the thickness of the clogging layer (Wolf et al. 2005, 2007 considered B to be equal to 0.1 m in NEIMO, their network infiltration and exfiltration model), K [m/day] is the hydraulic conductivity of the clogging layer (Wolf et al. 2005 mentioned that typical values of this parameter have been reported to be between 0.15 and 33.09 m/day in the literature and values between 7.34 and 29.37 m/day were found during their calibration of NEIMO), ΔH [m] is the hydraulic head difference between the water level in the sewer and the hydraulic head of the surrounding groundwater (taken to be null), and $\%_{\mathrm{leaks}}$ is the percentage of the leaky area from the total area generated by the wetted perimeter.

Zone 2: sewers located partially or totally in the aquifer. These sewers are modeled using the Cauchy boundary condition type using the leakage factor approach. Assuming that each sewer conduit has a uniform conductance, the exchanged flow rate between groundwater and the sewer is given by:

$$Q = C \times [h - \max(H, Z_{\mathrm{SW}})] \times L \qquad (2)$$

where Q [L^3/T] is the exchanged flow rate between the sewer conduit and the aquifer system (taking positive
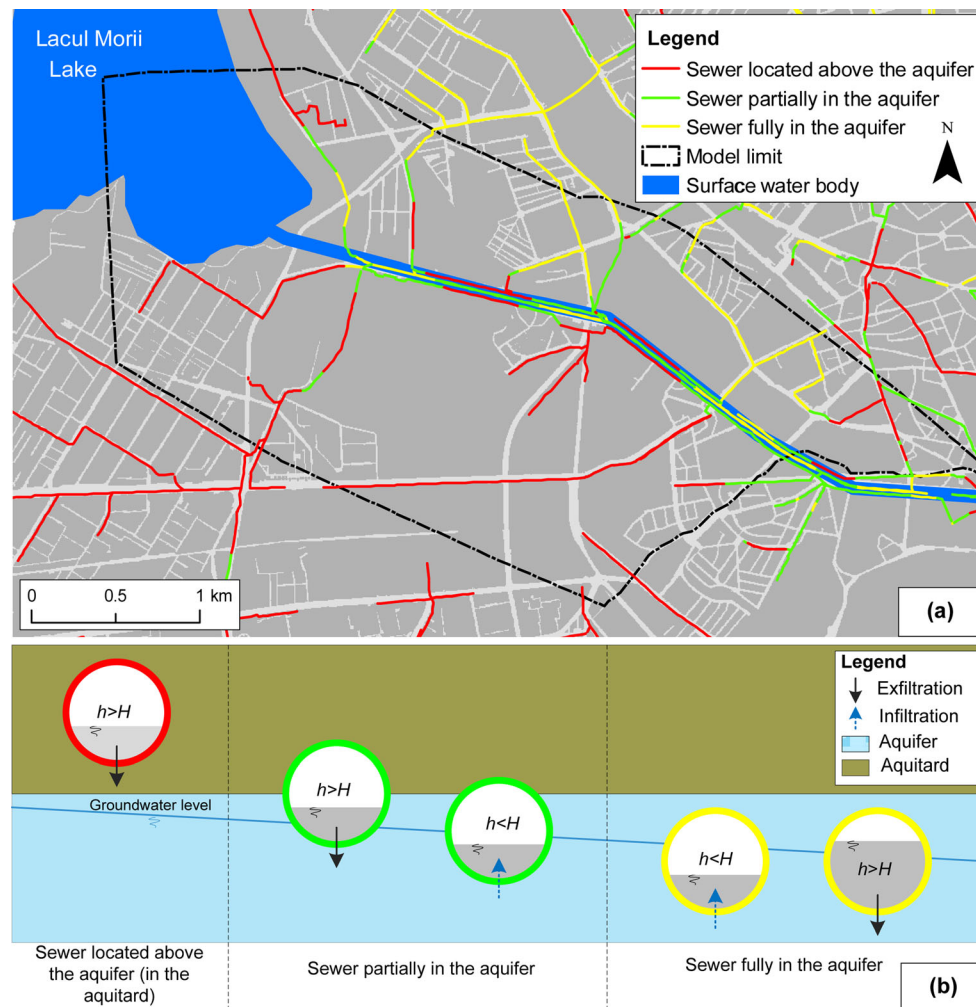
Fig. 8 **a** Sewer conduits mapped as a function of their position in the aquifer system, **b** diagrammatic vertical sections (H is the hydraulic head in the surrounding aquifer system; h is the hydraulic head in the sewer)

values for exfiltration and negative for infiltration); C [L^2/T/L] is the sewer conduit conductance per unit of length; H [L] is the hydraulic head in the surrounding aquifer system; h [L] is the hydraulic head in the sewer; Z_{SW} [L] is the elevation of the base of the sewer, and L [L] is the sewer length.

Considering the large number of sewer conduits, it would be challenging to define one conductance for each of them. In order to reduce the complexity of the problem, the sewer conduits are grouped into classes based on their structural and/or hydraulic properties. For example, by taking the sewer conduit cross section as a classification property, the sewer conduits with the same class of cross-sectional area are considered to have the same conductance. More conductance classes can be obtained by regrouping the sewer conduits based on age classes and material categories. For the present study, due to the insufficient amount of available data, only the sewer conduit's wetted perimeter (calculated as a function of the water level in the conduit) classification is taken into account.

The conductance value for each class for a given scenario (water level in sewers) is quantified by means of inverse calibration techniques. However, in order to ensure that the solutions of the automated calibration are realistic, it is considered necessary to provide ranges of variation by conditioning the accepted solutions of the conductance for each class and for each analyzed scenario. This can be done using the following expression:

$$\frac{K_{min} \cdot W_p \cdot (\%_{leaks})_{min}}{B} \leq C \leq \frac{K_{max} \cdot W_p \cdot (\%_{leaks})_{max}}{B} \quad (3)$$

where K_{max} [L/T] and K_{min} [L/T] are the assumed maximal and minimal values of the hydraulic conductivity of the clogging layer, W_p [L] is the wetted perimeter of the sewer, B [L] is the thickness of the clogging layer, and $(\%_{leaks})_{max}$ and $(\%_{leaks})_{max}$ are the assumed maximal and minimal percentages of the leaky area from the total area generated by the wetted perimeter.

As shown in Fig. 1, the study zone is crossed by a lined channel, the Dâmbovița River. The *main sewer collector*, located under the river, is composed of two rectangular-shaped sewer conduits and a drain (Fig. 2). The structure represents a complex system. Modeling the effects of this system on groundwater can be done in two ways:

1. *Combining the drain and the two rectangular-shaped sewers*. Taking account of their position compared to the aquifer system, the two rectangular sewer conduits are modeled using the aforementioned sewer modeling approach (using Cauchy boundary condition type if they are partially or totally in the aquifer unit and as a recharge rate otherwise). Thus, the main collector will be modeled using two elements under a Cauchy/recharge rate boundary condition combined with a drain effect. The drain effect can be implemented mathematically either as a specified discharge flow rate (when the discharge flow rate into the drain is known) or using a Cauchy boundary condition.

2. *Considering the overall system as a drain only*. Given that for the construction of the main collector, a trench with gravel bedding was set up (Fig. 2), it is justified to assume that in the case of sewage exfiltration from the rectangular sewers, the gravel bedding will drain these water flows and will discharge them into the left-side drain. Consequently, the overall system will act as *one drain* by draining both groundwater and the water exfiltrated from the two rectangular-shaped sewer conduits.

Subway tunnels and stations

The study zone is crossed by subway tunnels (Fig. 1) representing the segments of two subway lines: Magistrala 1 (M1) and Magistrala 3 (M3). These tunnels act on groundwater as (1) drains considering the infiltrating groundwater, and as (2) horizontal flow barriers totally or partially obstructing the natural flow condition leading to differential fluctuation (upstream and downstream relative to the barrier) of the groundwater level.

1. *Drain effect*. This effect is modeled as a linear discharge rate using the observed infiltration rates (varying from 45 to 76 m^3/day/km of tunnel length) reported by the Bucharest subway operator.

2. *Barrier effect*. This effect is modeled using the Horizontal Flow Barrier package (HFB) of MODFLOW (Harbaugh et al. 2000) software, which is a package that requires the introduction of the 'hydraulic characteristic', which corresponds to the ratio of the barrier material transmissivity to the barrier thickness. To cover all possible situations, consider the case of a barrier (Fig. 9), for which its height is b, its thickness is a and its material hydraulic conductivity is K_b, partially penetrating a confined aquifer with hydraulic conductivity K and a thickness B. The hydraulic characteristic (HC) that will be used to
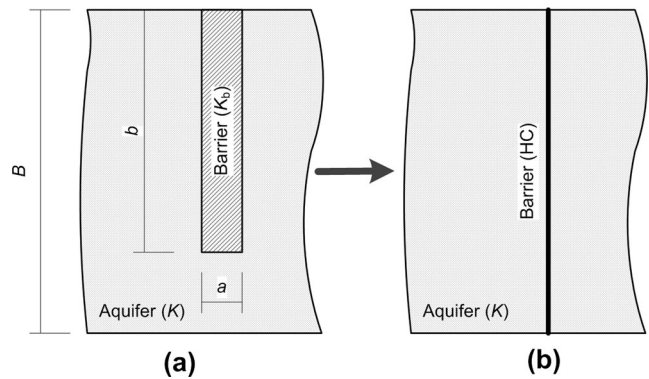

Fig. 9 Modeling approach of the horizontal flow barrier for the **a** general case and **b** horizontal flow barrier (HFB) model

model the barrier effect is computed (Boukhemacha et al. 2013) by using the following formula:

$$HC = \frac{T_{eq}}{a} = \frac{b \times K_b + (B-b) \times K}{a} \quad (4)$$

where, T_{eq} [L^2/T] is the equivalent transmissivity transforming the partially penetrating barrier into a fictitious one fully penetrating the aquifer, and HC [L/T] is the hydraulic characteristic of the fictitious barrier that will be used to model the tunnel's horizontal barrier effect.

The HC values that will be used in the groundwater flow model will be estimated by means of inverse calibration. Constant values of HC are considered for the tunnel segments (between two subway stations).

Water supply network (WSN) losses

The estimation of the groundwater recharge from the WSN losses is done by considering a uniform areal distribution of the total leakage rate. According to the water operator, at the scale of Bucharest, 1.7 m^3/s of the total technical losses (estimated to be about 2.4 m^3/s for 2013) contributes to the aquifer recharge. Thus, a groundwater areal recharge rate of 1.2 mm/day coming from the losses of the water supply system was adopted for the flow model. The uniform distribution of this recharge-rate was assumed due to the lack of spatial distribution of the losses from the WSN.

Groundwater recharge from precipitation

Groundwater recharge from precipitation was estimated using the Soil Conservation Service (SCS) model (United States Department of Agriculture 1954). As a function of the land-use, the following values of the areal recharge rates were taken: (1) 1.3 mm/day for areas covered by up to 50 % vegetation, (2) 1.6 mm/day for areas covered by up to 70 % vegetations and trees, and finally (3) 0.4 mm/day for the constructed areas.

Groundwater modeling and scenario development

After the analysis of the available data for the present study, it was decided to elaborate a single-layer two-dimensional (2D) flow model under steady-state conditions. The model is integrated by a finite difference method using MODFLOW (Harbaugh et al. 2000) modeling software.

The water level in Lacul Morii Lake (84 m asl) is used as a specified head boundary condition for the hydrogeological flow model. A similar boundary condition was obtained from hydraulic head measurements in geotechnical and hydrogeological boreholes located along a planned subway line (Magistrala 5; Fig. 1). The NW–SE model boundaries (boundaries parallel to Dâmboviţa River) were considered as no-flow boundaries.

In order to take into consideration a large range of cases of water level in each sewer, three scenarios were considered for the current study:

- *Scenario 1: low water level in sewers.* The water level in the sewers is taken to be one third of the sewer height
- *Scenario 2: medium water level in sewers.* The water level in the sewers is taken to be one half of the sewer height
- *Scenario 3: high water level in sewers.* The water level in the sewers is taken to be equal to the sewer height.

Furthermore, for each one of these modeling scenarios (corresponding to low, medium, and high water levels in the sewer system), both main sewer collector (MSC) modeling modes will be adopted, which will allow the assessment of the reliability of these modes.

The model calibration against point-wise hydraulic head data was done by means of combined trial-and-error and inverse calibration techniques. For each trial-and-error iteration, a value of the product of the leakage area from the total wetted area of the sewers ($\%_{\text{leaks}}$) and the hydraulic conductivity of the clogging layer is assumed and used to calculate exfiltrated flow rates of the sewer conduits located above the aquifer unit Colentina (using Eq. 1). The obtained model is then integrated by an inverse modeling approach to determine the spatial distribution of the hydraulic conductivity values by the pilot points method and to compute the values of the conductance of the sewer conduits modeled using the Cauchy boundary condition (sewers partially or totally in the aquifer unit); thus, each trial-and-error iteration is calibrated automatically. The selection of the appropriate solution, among the conducted iterations, is done by performing the flow budget at the level of the entire sewer system. Here the sum of the infiltration and exfiltration flow rates are compared to the flow rate value measured at the input of the wastewater treatment plant (WWTP). This flow rate value, resulting from the interaction between the groundwater and the sewer system, can be estimated using several flow methods, for example: the method of dry weather flow (Brombach et al. 2002), the moving minimum method (Weiß et al. 2002), the density average

method (Ertl et al. 2002), and the Swiss method of minimum night flow (Hager et al. 1984). Such methods are based on decomposing the dry weather flow into a fraction of strict wastewater and a fraction of infiltration.

Due to the lack of direct measurements at the scale of the pilot zone, the flow rate value resulting from the interaction between the groundwater and the sewer system will be extrapolated from the water operator estimations for the entire city. At the scale of Bucharest, based on direct flow measurements and dry weather flow-method estimations, the water operator estimates that the infiltration into the sewer system is higher than exfiltration (leakage).

The parameters used in conditioning (as presented in Eq. 3) the calibration of models in terms of the conductance of the sewers located partially or totally in the aquifer unit are summarized in Table 1. These parameters produced C_{min} values in the range of 1.4×10^{-5} to 1.8×10^{-3} m²/day/m and C_{max} values between 0.14 and 17.8 m²/day/m. As for the sewers located in the superficial deposits, the exfiltration flow-rate (calculated using Eq. 1) calibration was conducted using parameters within the same ranges of variation given in Table 1.

Groundwater level data

The automatic calibration relies on a set of head observation data points (Fig. 1). This set consists in the following two subsets:

- *Measured observation data points.* Obtained from direct field measurements. To these points were assigned observation weights equal to 2.
- *Interpolated observation data points.* These deduced observation points were obtained from a preliminary piezometric map constructed using the available direct observation data (measured values). These result from linear interpolation between pairs of measured observed data. Their location is conditioned by the existing measured observation data. The use of these deduced data aims to increase the density of the observation data set and to provide a number of observations higher than the number of parameters that have to be estimated from inverse modeling. The so-obtained points were associated with observation weights equal to 0.5.

Furthermore, a groundwater monitoring system was implemented in Bucharest. The system consists of a set of 51 piezometers (among which 29 have screens in Colentina aquifer and 22 in Mostistea aquifer). These piezometers provide hydraulic-head time-series observation data that will be used to calibrate transient flow models for Bucharest based on the proposed conceptual approach.

Table 1 Ranges of variation for the parameters used during the calibration of the sewer-system elements

Parameter	K_{min} [m/day]	K_{max} [m/day]	$(\%_{\text{leaks}})_{\text{min}}$	$(\%_{\text{leaks}})_{\text{max}}$	B [m]
Value	0.1	50	0.005 %	0.1 %	0.1

Table 2 Mean hydraulic conductivity values used for the lithological description (CCIAS 2012)

Lithology	Boulders	Gravels	Coarse sands	Medium to coarse sands	Medium sands	Medium to fine sands	Fine to medium sands	Fine sands	Clayey fine sands
Number of tests (well capacity)	313	170	28	30	17	7	29	40	13
K_{mean} [m/day]	233.67	175.04	62.96	58.83	38.92	35.17	34.40	20.89	13.72

Hydraulic characterizing of the aquifer

Since the model is elaborated in steady state with one aquifer layer only, the hydraulic characterization of the aquifer has to be done in terms of horizontal hydraulic conductivity. In the present study, the spatial distribution of the hydraulic conductivity is determined by using the pilot points method. This method requires pre-estimated values of the hydraulic conductivity at several points. In the current work, these values are estimated on the basis of the lithological description of the entire set of boreholes used for the elaboration of the 3D geological model of the study zone. The pre-estimation relies on computing the equivalent hydraulic conductivity of multiple horizontal sub-layers using the mean K values given by Table 2. These mean values were obtained from the analysis of a set of 647 well-specific-capacity tests conducted on the Quaternary sediments of the southeastern part of Romania (CCIAS 2012).

Results

The modeling results of the three scenarios (function of the sewer water levels) are presented. These were analyzed using two ways of modeling the complex system of the main sewer collector and its drain, producing a total number of six modeling scenarios. A better approach than the trial-and-error iteration for the studied pilot zone could be obtained using larger datasets of sewer system flow budget, as discussed in the model calibration section. However, to demonstrate the capability of the proposed conceptual approach, a qualitative quantification procedure of the sewer system budget in terms of its interaction with the groundwater is applied. The water operator in Bucharest estimated total (at the city's WWTP level) groundwater infiltration into the sewer system of about 1.88 m³/s. Considering that these estimations relied on dry weather flow results, one should take into consideration that the reported infiltration rate represents the algebraic sum of the exchanged flow rates (infiltrated and exfiltrated flow rates) between the sewer system and the aquifer system. By assuming a uniform distribution of these infiltrated rates for the entire city, one can assume that the pilot zone has contributed to the infiltration flow rate into the sewer proportional to the ratio between the area of the study zone and the area of the city. This leads to a total infiltration flow rate of about 0.08 m³/s for the pilot zone, which provides a convergence criteria ($\sum |Q_{infiltration}| - \sum |Q_{exfiltration}| \rightarrow 0.08$ m³/s) for the trial-and-error calibration procedure.

The modeling results in terms of sewer system flow budget are compared to the estimated (0.08 m³/s) ones (see Fig. 10). A comparison between observed hydraulic head data used for the model calibration and computed hydraulic head is given by Fig. 11. Figure 12 shows the hydraulic head maps for the entire set of modeling scenarios.

In all the scenarios and MSC modeling modes, the hydraulic head maps (Fig. 12) indicate clearly that the manmade structures (subway tunnels, cut-off wall, etc.) disturb the natural groundwater flow conditions and the hydrological cycle—for instance, the barrier effect associated with the subway tunnels can be observed via an increased groundwater level upstream of the tunnels and a decrease of the level downstream. Furthermore, the drain effect due to groundwater infiltration into the sewer system can be observed via a local decrease of groundwater level around conduits located within the aquifer.

Discussion in terms of the main sewer-collector-modeling mode

A comparison of the hydraulic head maps (Fig. 12) of the main sewer-collector-modeling mode indicates that:

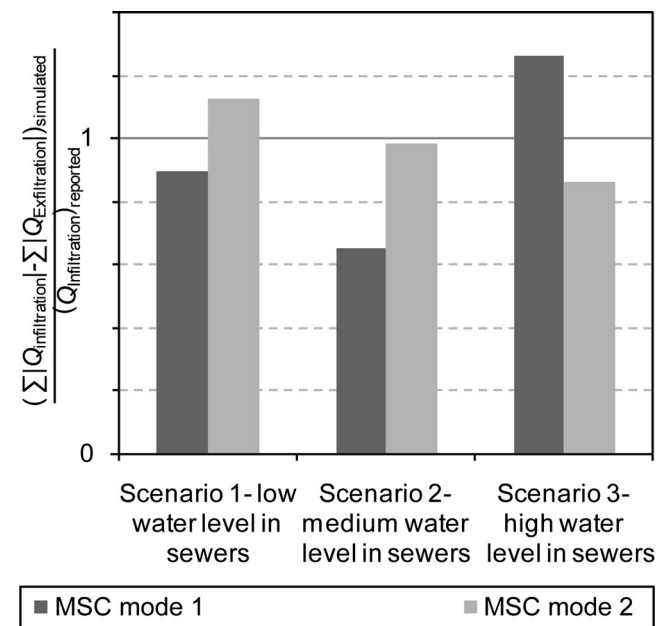- For the sewer water-level scenarios 1 and 2, the use of the first option for modeling the effect of the main

Fig. 10 Comparison between simulated flow budget in the sewer system and the estimated flow budget
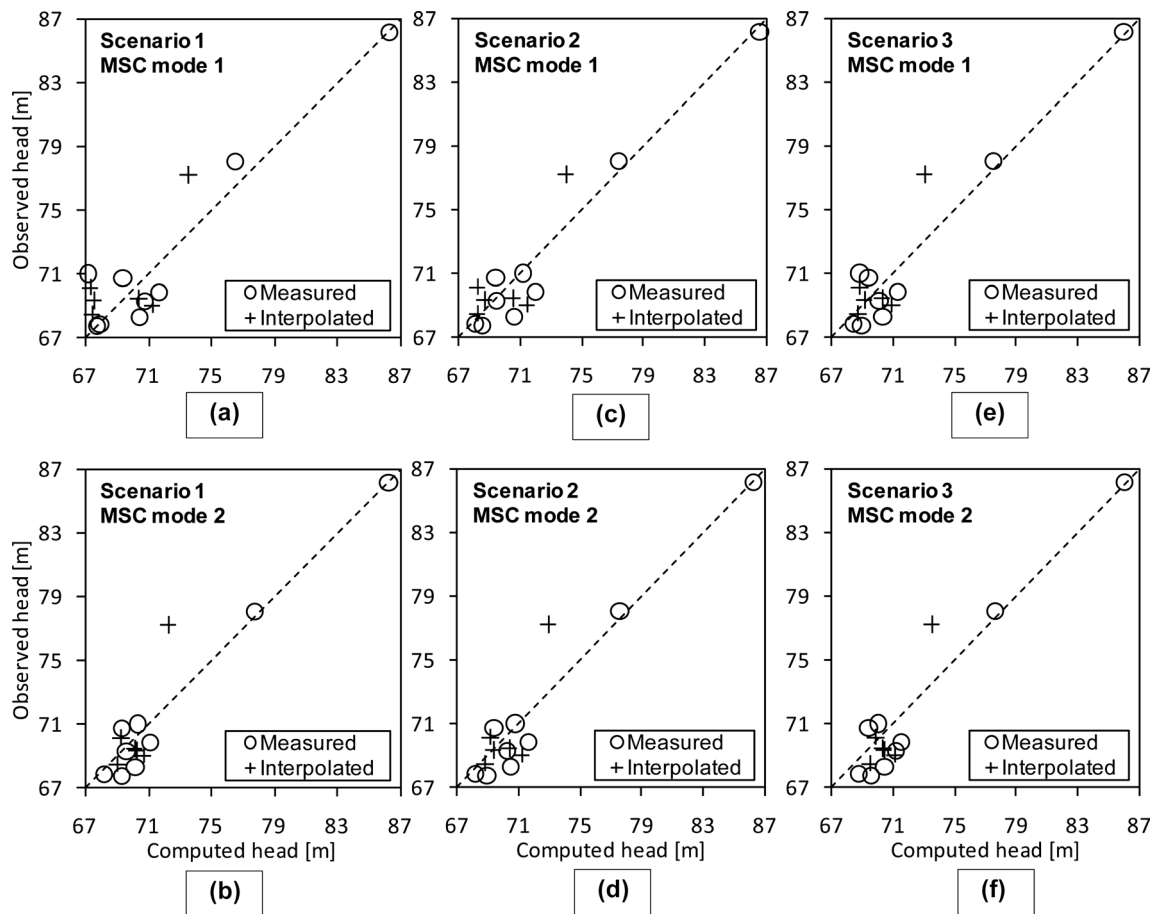
Fig. 11 **a–f** Comparison between computed and observed head data for the three scenarios and both main sewer collector (MSC) modeling modes; *mode 1*: modeling the main sewer collector by combining the drain with the two rectangular-shaped sewers, *mode 2*: modeling the main sewer collector by considering the overall system as a drain only

sewer collector (MSC modeling by combining the drain with the two rectangular-shaped sewers – MSC mode 1) leads to elevated hydraulic head values (up to 140 m) in the northern part of the study zone downstream of the Lake Lacul Morii cut-off wall (Fig. 12a,c,e). These results mean that the area located in the northern part of the study zone (limited by the cut-off wall and two subway tunnels) would be flooded. In reality, this is not the case.

- Different results were obtained in the case of the scenario 3 simulation (Fig. 12e). This is due to the lower exfiltration flow rate used for the sewer conduits located above the aquifer unit and was a direct consequence of the elevated water level in the sewer that was assumed for this scenario (which has led to reduced values of the sewers' conductance after calibration).

The comparison of the computed sewer flow budgets (Fig. 10) to the observed budget indicates that the second MSC modeling mode (MCS mode 2) gives better predictions than the first one.

In terms of observed hydraulic head data, no concrete conclusions can be made from the comparison presented in Fig. 11. Both modeling modes performed similarly at the given observation points. The results indicate that the second

mode for modeling the main sewer collector (MSC mode 2) gave better results than the first one. This can be explained by the high hydraulic conductivity of the bedding materials used to fill the sewer trench compared to the aquifer geologic materials as well as being due to the presence of the main sewer collector drain within this trench.

Discussion in terms of sewer water-level scenarios

By considering only the second MSC modeling mode (MSC mode 2), in terms of sewer water level scenarios, the sewer flow budgets comparison (Fig. 10) indicates that:

- Scenario 2 (corresponding to a medium water level in the sewers) gave the best results. This is to be expected, since assuming a medium water level in the sewer is the most conservative modeling approach of the three used.
- Scenario 1 (corresponding to a low water level in the sewers) overestimated the infiltrated flow rates. This indicates that its predictions gave a larger difference between the $\sum Q_{infiltration}$ and $\sum Q_{exfiltration}$. These results are coherent since a lower water level in the sewer increases the groundwater infiltration.
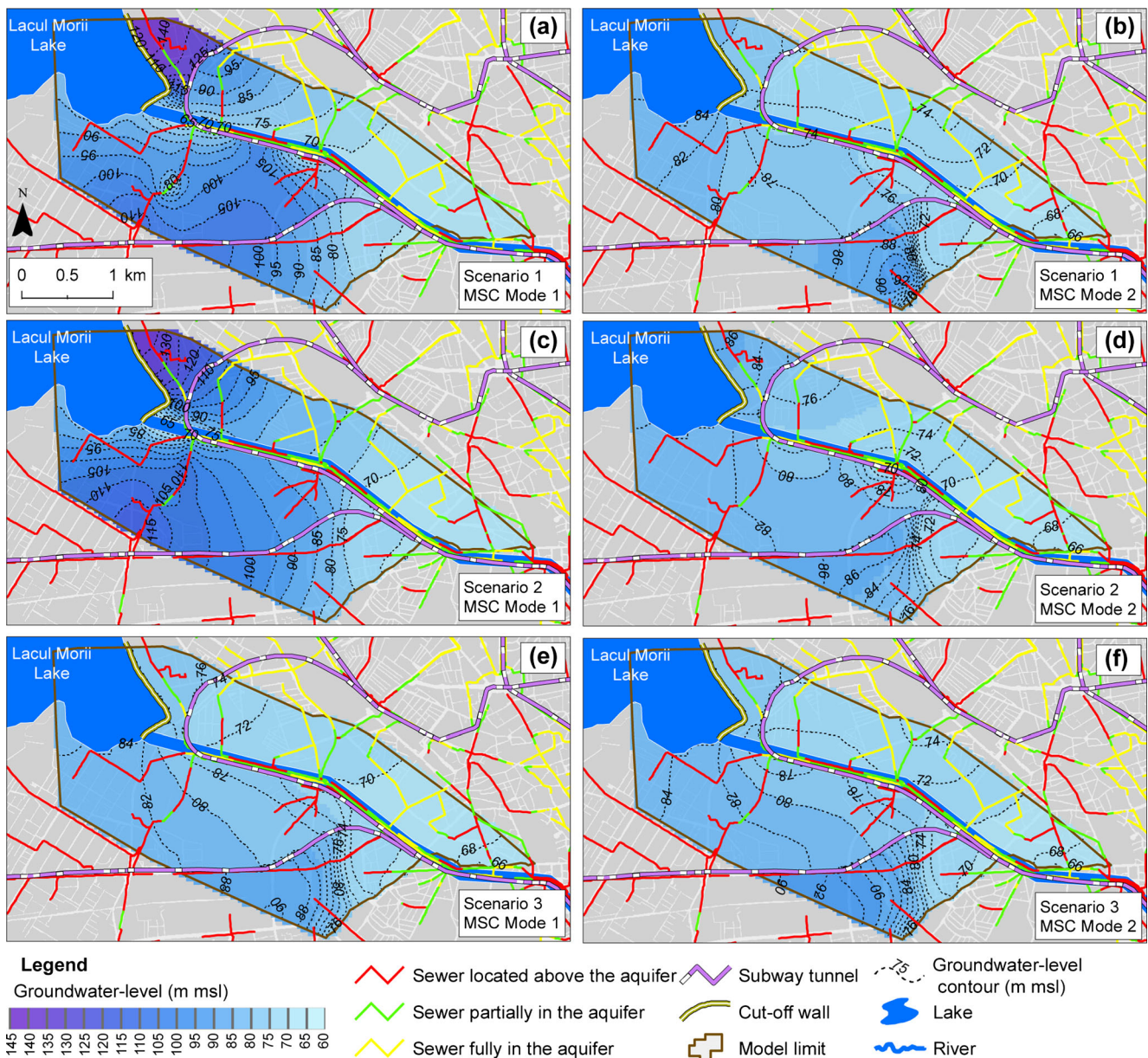
Fig. 12 **a–f** Hydraulic head maps for the three scenarios and both main sewer collector (MSC) modeling modes; *mode 1*: modeling the main sewer collector by combining the drain with the two rectangular-shaped sewers, *mode 2*: modeling the main sewer collector by considering the overall system as a drain only

- Scenario 3 (corresponding to a high water level in the sewers) underestimated the infiltrated flow rates. This indicates that its predictions gave a smaller difference between the $\sum Q_{\mathrm{infiltration}}$ and $\sum Q_{\mathrm{exfiltration}}$. These results are coherent since higher water level in the sewer decrease the groundwater infiltration.

Under the estimated flow budget in the sewer system, using the second mode of modeling the MSC effect and for a medium water level in the sewer system, the following recharge and discharge characteristics of the groundwater flow budget are found:

- The sewer system contributes with a recharge of about 53 % for groundwater.

- The groundwater discharge is about 76 % into the sewer system.
- The water supply network contribution as recharge for groundwater is about 18 %.
- Infiltration from precipitation represents a groundwater recharge of about 10 %.
- In the subway tunnels there is a reduced discharge percentage (less than 1 %) but a clear barrier effect on the flow paths.

These results clearly indicate the disturbance of the natural hydrological cycle, since more than 71 % of the groundwater recharge is from man-made sources (sewer system and water supply network) and more than 77 % of discharge is associated to non-natural

sinks (mainly the sewer system and the drain of the main sewer collector).

Furthermore, exfiltrated sewage is an indicator of groundwater contamination with substances such as nitrate, nitrite, phosphorous, chloride, boron and bacteria and others. This points toward a negative qualitative impact of the interaction between groundwater and the sewer system.

The resulting groundwater flow budget of the pilot zone possibly reflects important aspects of the future groundwater situation:

- Future reduction of the water supply network losses (which are estimated to contribute about 18 % to the Colentina aquifer recharge) could lead to a decrease of the groundwater level. This in turn will reduce groundwater infiltration into the sewer system and will increase sewage exfiltration. As a consequence, the reduction of the WSN losses will provide an indirect benefit for the wastewater treatment plant (by reducing the wastewater treatment costs and increasing the plant's efficiency) and it will negatively impact groundwater quality.
- Rehabilitating the sewer system will produce a strong impact (by disturbance of the actual groundwater flow dynamics and possibly inducing the intrusion of low-quality shallow groundwater into the higher-quality deeper groundwater, and others) on groundwater. Such a measure has to be closely studied in order to manage its impact on groundwater as well as on the existing urban structure and infrastructure. The consequent rise of groundwater level could create/accentuate uplift phenomena, affect the structural integrity and durability of civil works, and increase the risk of internal erosion.

Summary and conclusions

Groundwater system management becomes more and more necessary, particularly in urban environments because of continuously increasing urbanization, industrialization and exploitation. Such management can be reliably supported by means of mathematical modeling combined with geospatial databases.

The present study was conducted in the spirit of elaborating a conceptual approach to study the urban groundwater system flow in Bucharest. The proposed approach takes into consideration several urban infrastructure elements that can be found in modern cities such as sewer systems, subway tunnels and the WSN. The study focuses on the interaction between sewer systems and groundwater. An adaptation of the leakage factor approach was proposed by making use of the notion of zoning the sewers systems. Considering the sewer conduit position in an aquifer system (infiltration/exfiltration or pure exfiltration), its expected behavior could be predicted. Also, the applicability of the proposed wetted-perimeter-based classification for sewer systems was shown.

As an application, a single-layer steady-state flow model, relying on the developed conceptual approach, was built for a pilot zone in Bucharest. Within the study area perimeter, no urban elements go deeper than the Colentina aquifer, and the Intermediary Deposit aquitard does not pinch out (no direct natural hydraulic connection between the upper two aquifers), so the limitation of the model to a single layer is not believed to have a strong impact on the obtained results. However, it should be noted that the sewer conductance values depend on the structural and hydraulic state of the sewer system as well as on the hydrogeological conditions. Thus, the obtained conductance values are valid under similar conditions to those used for the model's calibration.

The application reflected the capabilities of the approach in question, even though the study was more qualitative due to the limited amount of data available. The analysis of the modeling results highlighted the possibility of quantification of the interaction between groundwater and the different urban infrastructure elements, particularly with the sewer system. The modeling results show the following:

- Disturbance of the natural hydrological cycle with significant percentages of groundwater recharge and discharge has been found to be associated with man-made infrastructure elements (sewer systems, water supply networks, subway tunnels).
- Groundwater level fluctuation is induced by the change in the type of land cover and land use, through the construction of flow barriers (tunnels and cut-off walls) and other man-made features.

The study of the selected zone's specific features, including the complex structure of the main sewer collector, allowed the choice of an adequate modeling mode (the overall effect of a drain) for the system in question. The described methodology combined with the ongoing implementation of the groundwater monitoring system will allow for the elaboration, calibration, and the validation of a groundwater flow model at the scale of that of the city of Bucharest.

References

Al-Rashed MF, Sherif MM (2001) Hydrogeological aspects of groundwater drainage of the urban areas in Kuwait City. Hydrol Process 15(5):777–795. doi:10.1002/hyp.179

Boukhemacha MA, Gogu CR, Serpescu I, Gaitanaru D, Bica I, Diaconescu A, Brusten A (2013) Hydraulic characterizing of tunnel's barrier effect for groundwater flow modeling:

application for Bucharest city. 13th SGEM GeoConference on Sci and Technol in Geology. Explor Min 2:179–186. doi:10.5593/SGEM2013/BA1.V2/S02.024

Brombach H, Weiß G, Lucas S (2002) Temporal variation of infiltration inflow in combined sewer systems. In: 9th International Conference on Urban Drainage, Portland, OR, September 2002

CCIAS (2012) 3D geological models and spatial ditribution of the hydraulic properties. Research report, SIMPA project: sedimentary media modelling platform for groundwater management in urban areas. Technical University of Civil Engineering of Bucharest, Groundwater Engineering Research Center (CCIAS), Bucharest

Ertl TW, Dlauhy F, Haberl L (2002) Investigations of the amount of infiltration inflow into a sewage system. 3rd International Conference on Sewer Processes and Networks, Paris, April 2002

Gogu R, Velasco V, Vázquez-Suñe E, Gaitanaru D, Chitu Z, Bica I (2011) Sedimentary media analysis platform for groundwater modeling in urban areas. In: Lambrakis N, Stournaras G, Katsanou K (eds) Advances in the research of aquatic environment. Springer, Heidelberg, Germany, pp 489–496

Gustafsson GL (2000) Alternative drainage schemes for reduction of inflow/infiltration: prediction and follow-up of effects with the aid of an integrated sewer/aquifer model. 1st International Conference on Urban Drainage via Internet, Prague, Czech Republic, 2000

Hager WH, Bretscher U, Raymann B (1984) Methoden zur indirekten Fremdwasserermittlung in Abwassersystemen [Methods for indirect determination of extraneous water in sewage systems]. Gas-Wasser-Abwasser 64(7):450–561

Harbaugh AW, Banta ER, Hill MC, McDonald MG (2000) MODFLOW-2000, the U.S. Geological Survey modular ground-water model: user guide to modularization concepts and the ground-water flow process. US Geol Surv Open-File Rep 00-92

Liteanu E (1952) Geologia zonei orasului Bucuresti [Geology of the Bucharest area]. Com. Geol., Inst. Geol., Bucharest

Martinez SE, Escolero O, Wolf L (2010) Total urban water cycle models in semiarid environments: quantitative scenario analysis at the area of San Luis Potosi, Mexico. Water Resour Manag 25 (1):239–263. doi:10.1007/s11269-010-9697-6

Nakayama T, Watanabe M, Tanji K, Morioka T (2007) Effect of underground urban structures on eutrophic coastal environment. Sci Total Environ 373(1):270–288. doi:10.1016/j.scitotenv.2006.11.033

Popescu C, Lăzărescu F (1988) Contcepția generală de amenajare complexă a râului Dâmbovița în municipiul București [General concept of the Dambovita River channel-modification works in Bucharest city]. Hidrotehnica 33(1):3–9

Rauch W, Stegner T (1994) The colmation of leaks in sewer systems during dry weather flow. Water Sci Technol 30(1):205–210

Rueedi J, Cronin AA, Morris BL (2009) Estimation of sewer leakage to urban groundwater using depth-specific hydrochemistry. Water Environ J 23(2):134–144. doi:10.1111/j.1747-6593.2008.00119.x

Serpescu I, Radu E, Gogu CR, Boukhemacha MA, Gaitanaru D, Bica I (2013) 3D geological model of Bucharest city Quaternary deposits. 13th SGEM GeoConference on Sci and Technol in Geology. Explor Min 2:1–8. doi:10.5593/SGEM2013/BA1.V2/S02.001

Shiklomanov I (1993) World fresh water resources. In: Gleick H (ed) Water in crisis: a guide to the world's fresh water resources. Oxford University Press, New York, pp 13–14

United States Department of Agriculture (1954) National engineering handbook. US Department of Agriculture, Washington, DC

Vázquez-Suné E, Sanchez-Vila X (1999) Groundwater modelling in urban areas as a tool for local authority management: Barcelona case study (Spain). Impacts of Urban Growth on Surface Water and Groundwater Quality, IUGG 99 Symposium HS5, Birmingham, UK, July 1999

Weiß G, Brombach H, Haller B (2002) Infiltration and inflow in combined sewer systems: long-term analysis. Water Sci Technol 47(7):11–19

Wolf L, Klinger J, Schrage C, Mohrlok U, Eiswirth M, Hötzl H, Burn S, DeSilva Dh, Cook S, Diaper C, Correll R, Vanderzalm J, Rueedi J,Cronin AA, Morris B, Mansour M, Souvent P, Cencur-Curk B, Vizintin G, Voett U, Arras U, Höring K, Rehm-Berbenni C (2005) Assessing and improving sustainability of urban water resources and systems (AISUWRS). Final project report, Department of Applied Geology, Karlsruhe University, Karlsruhe, Germany

Wolf L, Eiswirth M, Hotzl H (2006) Assessing sewer–groundwater interaction at the city scale based on individual sewer defects and marker species distributions. Environ Geol 49(6):849–857. doi:10.1007/s00254-006-0180-x

Wolf L, Klinger J, Hoetzl H, Mohrlok U (2007) Quantifying mass fluxes from urban drainage systems to the urban soil–aquifer system. J Soil Sedimentol 7(2):85–95. doi:10.1065/jss2007.02.207