Modelling the hydrological impacts of a large-scale urban development project located in a shallow groundwater context: contributions of land-use modifications, underground infrastructures and stormwater infiltration

Modélisation hydrologique des impacts d'un grand projet d'aménagement au droit d'une nappe peu profonde : rôle des modifications de l'occupation du sol, des infrastructures souterraines et de l'infiltration des eaux pluviales

J. Sage[1*], F. Rodriguez[2,3], W. Pophillat[4], I. Braud[5], M-L Mosini[2,3], E. Berthier[1]

[1]Cerema, Equipe TEAM
[2]Université Gustave Eiffel, GERS-LEE
[3]IRSTV,FR CNRS 2488
[4]DREAL Occitanie
[5]INRAE, RiverLy
Corresponding author: jeremie.sage@cerema.fr

RÉSUMÉ

Cette étude analyse l'impact d'un grand projet d'aménagement dans un contexte de nappe peu profonde et de sous-sol peu perméable. L'analyse est réalisée à partir de modélisations numériques. Elle repose sur l'évaluation successive de l'impact sur les termes du bilan hydrologique et les niveaux de nappes de : i) la modification de l'occupation du sol, ii) l'introduction de nouvelles infrastructures souterraines (canalisations et systèmes de drainage des fondations) et iii) la mise en œuvre d'ouvrages perméables de gestion à la source des eaux pluviales. Les modifications d'occupation du sol conduisent à des effets spatialement contrastés sur la recharge et le niveau de la nappe, avec des hausses marquées sur les parcelles agricoles en raison de la disparition de drains (initialement présents) ainsi que de la diminution du couvert végétal, et donc de la transpiration. L'introduction d'infrastructures souterraines supplémentaires se traduit par un abaissement du niveau de la nappe, mais avec un impact très variable spatialement. L'infiltration des eaux pluviales est insuffisante pour réellement limiter les volumes rejetés en aval mais influence fortement le niveau de la nappe, avec des hausses s'étendant bien au-delà des ouvrages. L'étude souligne la nécessité d'anticiper l'impact combiné de l'urbanisation et de l'infiltration des eaux pluviales dans des contextes pour de tels contextes où des interactions avec la nappe sont attendues.

ABSTRACT

This study investigates the impact of a large-scale urban development project located in a shallow groundwater (GW) and low permeability context based on numerical modelling. The analysis is conducted by comparing water balance and groundwater levels simulated prior to the project with those obtained after successively accounting for i) land-use modifications, ii) introduction of new pipes and dewatering systems at building foundations and iii) implementation of sustainable drainage systems allowing infiltration (i-SUDS). Land use modifications produced contrasting effects on GW recharge and levels, with potential rise over former agricultural plots due to drains removal and reduction of transpiration via soil-sealing. The introduction of additional subsurface infrastructures markedly reduced groundwater levels, but the impact varied strongly across the site. I-SUDS provided only marginal runoff control but strongly influenced GW levels, with rises extending well-beyond their immediate vicinity. The study highlights the necessity and challenges of anticipating the combined impact of i-SUDS and urbanization in contexts where interactions with GW are to be expected.

KEYWORDS

Interactions; Low permeability contexts; On-site runoff control; Urbanization; Water balance

1 CONTEXT AND OBJECTIVES

Urbanization affects subsurface hydrology, with current literature showing contrasting impacts from a catchment to another (Bhaskar et al. 2016). This variety of outcomes arise from the complex balance between the reduction of infiltration and transpiration along with the introduction of source or sink terms within the underground compartment. The situation is further complicated in the presence of shallow groundwater (GW) and stormwater infiltration, due to increased interactions with underground infrastructures and near surface processes (Pophillat et al. 2022). In such contexts, modelling tools that allow assessing the effects of urbanization and stormwater management strategies can be valuable to prevent undesirable outcomes (e.g., excessive GW level rise or depletion; increased drainage by underground infrastructure; resurgences). Anticipating modifications of subsurface water is also becoming increasingly important given the growing pressure on water resources.

The URBS model, co-developed by Université Gustave Eiffel and Cerema, is one the few models that allows describing the interplays between surface hydrology, GW and underground structures, in particular at a sufficiently fine spatial resolution to capture the effect of the geometry and characteristics of urban features (Pophillat et al. 2021). This study presents an application of the model to a large-scale, real-world, and complex development project located in a low-permeability shallow GW context: the Moulon district within the Paris-Saclay Cluster. The objective is to examine the water-balance and GW impacts of the project, by differentiating the contributions of land use modifications, new of underground structures, and stormwater infiltration.

2 METHODOLOGY

2.1 Site and urban development project description

The Moulon district consists of a 330-ha development area within the Paris-Saclay R&I cluster (located ~20 km southwest of Paris). The present study focuses on 310 ha situated on a silty clay plateau overlying a shallow aquifer. The development of the site has been carried out progressively since 2014 and is still ongoing in some sectors (completion expected by 2027). The area was initially mainly agricultural and forested, but already hosted several research and higher education facilities. The development project leads to significant modifications of surface cover, but also affects the underground through the introduction of new infrastructures or the removal of existing drains on agricultural plots. A summary of these modifications is provided in Table 1.

Table 1. Surface and subsurface conditions at the start and end of the project. S_{nat}: unsealed areas, including woods, agricultural parcels and urban green spaces; S_{agr}: agricultural parcels area (drained at -1 m); S_{woods}: woods area; S_{imp}: impervious area (buildings and paved surfaces); $S_{i\text{-}SUDS}$: infiltration SUDS area; $S_{drain,\ build}$: extent of drainage from building foundations; $Z_{avg,\ drain}$: average drainage depth (from agricultural parcels and building foundations); L_{sewer}: length of sewer systems

Year	S_{nat}	S_{agr}	S_{woods}	S_{imp}	$S_{i\text{-}SUDS}$	$S_{drain,\ build}$	$Z_{avg,\ drain}$	L_{sewer}
2014	247 ha	134 ha	48 ha	67 ha	1 ha	4ha	1.1 m	14 km
2027	192 ha	50 ha	44 ha	110 ha	13 ha	12ha	1.5 m	24 km

Due to the site's location upstream of already densely urbanized valleys, controlling runoff on-site to avoid increasing downstream flood risk is a major concern. Following that, the challenge lies in managing stormwater under such unfavorable hydrogeological conditions. The adopted strategy combines: the implementation of green roofs on new buildings; the management of runoff from paved surfaces via a network of swales (where possible); and the conveyance of stormwater from the largest storms to large downstream storage basins. Overall, 88% of the impervious area is connected to pervious swales or basins (later denoted as i-SUDS), with an average ratio between connected impervious area and infiltration area of 18 (but reaching no less than 177 for retention basins located downstream the stormwater management system).

2.2 The URBS model

URBS can be described as physically-based, distributed urban hydrology model. Runoff production is simulated at the scale of unit elements defined from cadastral parcels. Each unit may incorporate 4 land-use profiles: green surfaces, paved surfaces, buildings and i-SUDS. Each of these profiles is described by the succession of the following compartments: tree canopy, surface and soil (distinguishing unsaturated and saturated zone). Processes accounted for at this scale include: interception; surface infiltration and evaporation; soil moisture redistribution; transpiration; and leakage from the potable water network. Surface units are subdivided in smaller elements to depict GW flows and interactions with burried infrastructures, i.e., seepage in sewer systems or drainage at building foundations. Further description of the model can be found in Pophillat et al. (2021).

2.3 Assessment strategy

This application builds on a previous study in which 9 "acceptable" sets of parameters were identified based on comparison with daily groundwater depth measurements from 6 piezometers. A complete description of the methodology is provided in Pophillat (2022). The impact of the site's development is analyzed by comparing water balance and groundwater levels simulated prior to the project with those obtained after successively accounting for the changes in land use, the introduction of new underground infrastructures, and, finally, the implementation of i-SUDS. Corresponding scenarios are denoted as: "Initial", "Surf. only", "No i-SUDS", "Future". By incrementally considering the site's modifications, the approach is expected to help identify the factors and mechanisms driving its hydrological response to urbanization. Each scenario involves specific geodata processing for the discretization of the modeling domain, the spatialization of land use and soil characteristics, and the introduction of underground features. Corresponding number of surface and subsurface discretization units ranges from 985 to 1.049 and from 2.963 to 11.150. The number of drainage network features is comprised between 1077 and 1725. For the geology, 3 formations – surface soil, silts, and rocky clay – are considered, each with a variable vertical extent across the domain. The complete "Future" scenario incorporates a total of 247 i-SUDS. Given the difficulty of precisely specifying their characteristics, a simple conceptualization is adopted: each solution is represented as a pervious storage unit with vertical sides and a fixed depth of 30 cm.

Simulations are conducted at a 6-min timestep for a 4-yr period (2011-2014) using rainfall and potential evapotranspiration (resp. 665 and 760 mm/yr) from a nearby climate station. Subsurface storage initialization is achieved by repeating the year preceding the simulation period until stabilization of GW levels and recharge.

3 RESULTS

Water-balance components and average GW levels (Z_S) simulated for the different scenarios are presented in Figure 1. The impact of the successive transition from one scenario to one other on average GW levels across the simulation domain are shown in Figure 2.

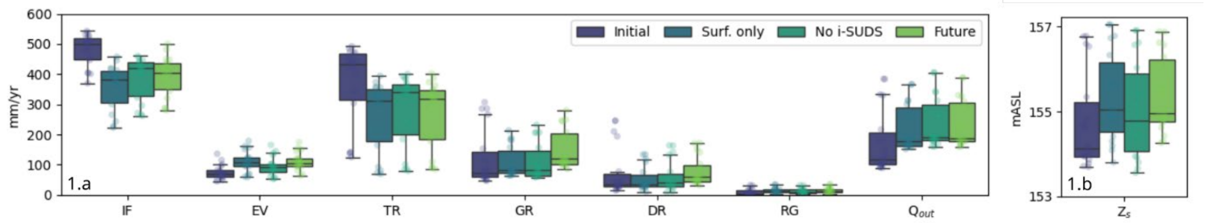

Figure 1: water balance and average GW level for the different scenarios (IF: infiltration; EV: surface evaporation, TR: transpiration; GR: GW recharge; DR: drainage by underground structures; Q_{OUT} discharge at the outlet of drainage system; Z_S : Average GW levels across the domain and over the simulation period).

For initial site conditions, the high infiltration (IF) and evapotranspiration (EV+TR), along with relatively low downstream discharge (Q_{out}) are consistent with the low impervious cover (S_{imp} = 22% of the total area). Expectedly, land-cover modifications translate into a decrease in IF and ET as well as an increase in Q_{out}. The changes, however, are not strictly proportional (nor directly or inversely) to the increase of S_{imp}, which can first be explained by land cover modifications not only affecting the surface but also the subsurface compartment – with for instance the loss of initially drained agricultural plots or reallocation of tree cover (influencing GW levels and thereby IF or TR). Overall, the changes in GW recharge (GR) remain limited due to a compensation between the reduction of IF and the reduction of TR. Consistently with the decline of agricultural areas, drainage (DR) decreases. As a consequence, simulations show a slight increase in resurgences (RG) and a more notable rise in Z_S (both mainly associated with formerly agricultural parcels). As shown in Figure 2a, this rise concentrates in the north-central part of the catchment where most agricultural plots are converted to urban parcels (undrained, with limited TR). Interestingly, a decrease in GW level is observed in the south-west part of the site, which can be mainly attributed to increased transpiration due to unsealing combined with tree planting.

The introduction of urban infrastructures brings down average GW levels closer to their initial values, leading to higher IF values, that in turn causes a slight increase in GR. This water table decrease exhibits a strong spatial variability (Figure 2b), with the largest impacts occurring below and at the vicinity of drained building foundations (see in particular the large rectangular building in the northern part of the site and GW level decrease downstream due to the barrier effect). Expectedly DR slightly increases, whereas other GW-related terms remain mostly unaffected (in line with the localized effect urban infrastructures). The increase in DR is partly translated in the Q_{out} that increases (despite higher IF).

Surprisingly, i-SUDS implementation produces contrasted impacts and, in several configurations, a decrease in IF compared to the “no i-SUDS” scenario. The explanation for this counterintuitive result essentially lies in the reduction of IF from other green spaces (up to -24%) caused by the water table rise (further exacerbated by the decrease in TR due to more frequent saturation of vegetation root profiles). Within i-SUDS, IF ranges between 630 to 1700 mm/yr, which is relatively low but consistent with the very poor permeability of the silt layer located 25 to 70 cm below the surface (between 10^{-8} and 10^{-7} $m.s^{-1}$). Due to these low permeability, i-SUDS experience extensive and long-lasting surface ponding, reflected by a modest increase in surface evaporation (EV). Despite the overall limited change in IF, the locally high values associated with i-SUDS translate into a strong increase in GR, resulting in a pronounced rise of GW levels in the sectors where i-SUDS are implemented (see Figure 2). The latter in turn causes a rise in both DR and RG. Finally, Q_{out} remain mostly unaffected, which reflects the cancellation of the runoff-reducing effect of i-SUDS by the increase in DR.

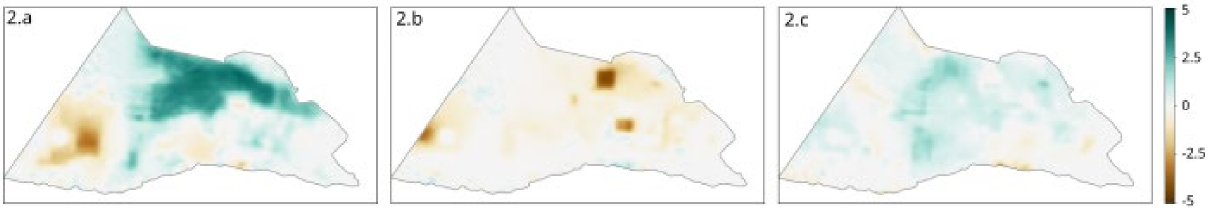

Figure 2: Time averaged GW level differences from a scenario to another (average across tested parameterizations). 2a: “Initial” to “Surf. Only”; 2b: “Surf. Only” to “No i-SUDS”; 2c: “No i-SUDS” to “Future”

4 CONCLUSIONS

The impact of a large-scale development project located in a low permeability and shallow GW context was analyzed based on numerical modelling. The main findings may be summarized as follows: land use modifications produce contrasting effects on GW recharge and levels; GW level rise may in particular occur over agricultural plots due to the removal of agricultural drains and the reduction of transpiration; subsurface infrastructures (pipes and dewatering systems) significantly lower GW level but their impact is highly variable in space; i-SUDS provide only marginal runoff control, fail to reduce downstream volumes due to increased drainage by underground structures, yet, they strongly affect GW levels, with rises extending well beyond their immediate vicinity. The study more generally illustrates the challenges associated with i-SUDS as well the complexity in anticipating the joint impact of i-SUDS and urbanization due to the complex and potentially very localized interactions between infiltration, transpiration, GW and underground structures. This model application provides a basis for further investigations. Model evaluation and parameterization could for instance be revisited in the light of updated site knowledge, including GW level and stormwater sewer flow measurement collected over the past 3 years during which large portions of the site had already been urbanized. Given their importance on this particular site, the conceptualization of the interactions between infiltration, transpiration and GW levels could also deserve further examination. Finally, while the use of modelling tools such as the one applied in this study appears promising for operational applications, further investigations are needed to understand how uncertainties related to the underground compartment or stormwater management features may influence the results, and to clarify whether the method remains applicable in contexts where such knowledge is limited.

REFERENCES

Bhaskar, A. S., L. Beesley, M. J. Burns, T. D. Fletcher, P. Hamel, C. E. Oldham, and A. H. Roy. 2016. “Will it rise or will it fall? Managing the complex effects of urbanization on base flow.” *Freshwater Science*, 35 (1): 293–310. The University of Chicago Press.

Pophillat, W. 2022. “Conséquences d’une systématisation des pratiques d’infiltration à la parcelle des pluies courantes à l’échelle de petits bassins versants urbains et péri-urbains – Apports de la modélisation intégrée.”

Pophillat, W., J. Sage, F. Rodriguez, and I. Braud. 2021. “Dealing with shallow groundwater contexts for the modelling of urban hydrology – A simplified approach to represent interactions between surface hydrology, groundwater and underground structures in hydrological models.” *Environmental Modelling & Software*, 144: 105144.

Pophillat, W., J. Sage, F. Rodriguez, and I. Braud. 2022. “Consequences of interactions between stormwater infiltration systems, shallow groundwater and underground structures at the neighborhood scale.” *Urban Water Journal*, 19 (8): 812–823. Taylor & Francis.