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## URBAN LAKES: FROM LACK OF REGARD TO SMART DEAL?

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### KEY WORDS

Groundwater, geographic information system, geological data modelling, finite element method, confluence, bathymetry, variogram, leakage, renewal time, water table flood.

### ABSTRACT

*This paper deals with hydrogeological modelling of urban alluvial lakes and flood hazard – Case of a 40 hectares gravel-pit lake located at the close upstream from confluence of the Seine and Marne rivers, Paris, France. A combined 3D approach is introduced through geographic information system (GIS), geological data modelling (GDM), finite element method (FEM), by using geological and topographic data and hydrodynamic monitoring. This methodology has both deterministic and statistical ability. The deterministic ability allows the model to provide optional design parameters for digital elevation model (DEM), lake artificial banks, sewers and foundations. The statistical ability can be used to model the geological layers of the urban underground and check the consistency between boreholes, DEM, layer interfaces and geological-map data. The purpose of the model is to help decision makers to choose a balanced set of actions in order to monitor the level of a gravel pit lake in a hyper-urbanised area of the Paris region. One consequence for water managers is that there is no need to invoke any intervention as rainwater drainage management. Water table rising hazard management in the floodplain of the Seine and Marne rivers is suggested.*

### 1. INTRODUCTION

All over the world, sand and gravel are dug up in great quantity for industrial or construction purposes [1]. In 2013, European demand gave rise to an estimated 15 billion euros annual turnover and 200,000 jobs. When aggregates were extracted under the piezometric head of the water table, a new lake, which is known as a “gravel pit lake” [2], appeared in the excavation. Gravel pit lakes are usually small (1-100 hectares) and shallow (2-12 meters), with some rare lakes being 40 meters deep. As gravel pit lakes occur in the alluvial plain of a river system, they are fed through the alluvial aquifer.

An accurate assessment of the hydrogeological functioning of this type of surface water body could foster an integrated strategy for decision making. Créteil Lake, which was created in the 1970s very close to the centre of the geological Paris Basin, is a case of a gravel-pit lake in an urban environment. Recent engineering concerns in hydraulic impacts on the neighbourhood and ecological issues prompted, in this case, the need to understand the monthly level variations observed and to estimate hidden transfers of this 40 hectares lake from and into the subsoil (sediments, alluviums, fills). More important in the long term is the questionable role the lake could play in flood hazard in the uppermost urbanized area of confluence from the Marne River to the Seine River (Figure 1). Is the lake an aggravating or buffering factor of flood?

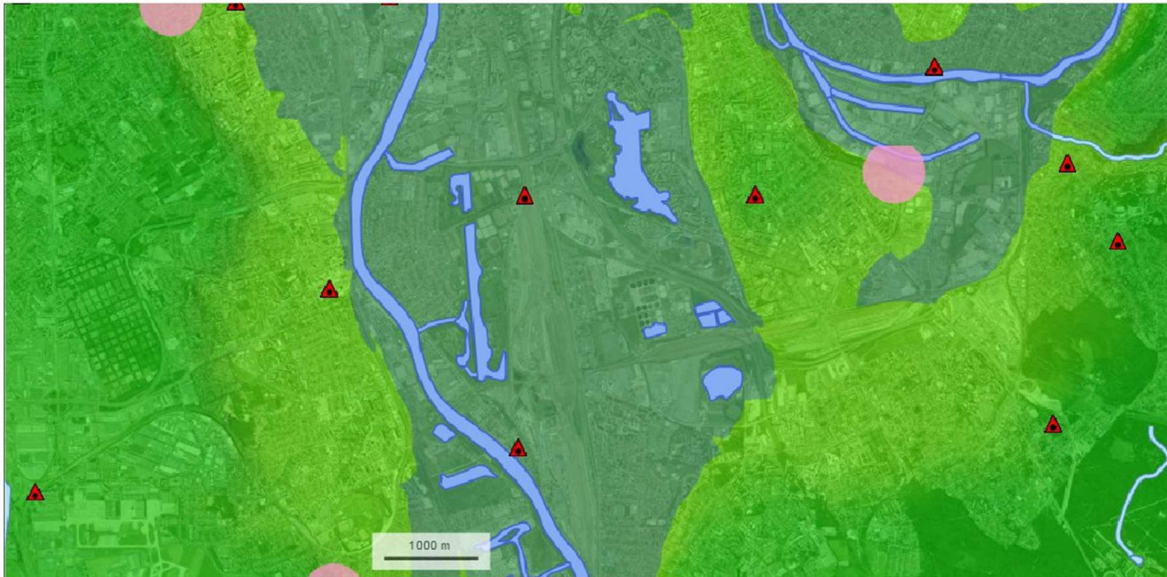
**Conceptual questions.** At first and after consultation of the documents available on the study area, this lake was believed to be a cross lake (inflow from groundwater and outflow make balance of the lake level). Progress during the study raised basic questions backwards. Is it really a cross lake or instead a terminal lake (water flows from all sides into the lake)? Where does the output flux go through (throughout the banks, into a rainwater collector, down to a deeper layer of rock...)? Is the input flux localised or distributed on the whole aquifer – lake interface or only a part of it?

**Quantitative questions.** The groundwater model should also help to answer a series of quantitative questions. Is a transfer rate coefficient necessary as a boundary condition to the groundwater model? Do

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underground structures embody some hydraulic obstacles to groundwater fluxes? What is the amount of the annual total flux, the input flux into the lake and its output flux? How much are the lake volume and, according to the annual flux, the residence time of water in the lake?



**Figure 1:** Map of the 100-year floodplain (dark green) of Seine River in the close upstream from Paris. Network of topographic markers (red, pink) in the study area around Créteil Lake. French Geodetic Survey (Geoportail © IGN).

## 2. BACKGROUND AND ISSUES: FROM QUARRIES TO URBAN LAKES

In France, the extraction of alluvial aggregates amounted to  $192 \times 10^6$  tons in 1970 (vs.  $18.6 \times 10^6$  in 1949), the production of the (geological) Paris Basin weighing 30% of national production. From 1982 to 1990 in Ile-de-France, the most inhabited region in France (12 million people in 2014; 1 001 person/km<sup>2</sup>; 52 800 euros GDP per capita), the production of alluvial aggregates from licensed extraction sites was 15.0 Mt. After a peak in 1990, the regional production recorded almost continuous decline until 2014 down to 6.0 Mt, mainly due to recession of building and public works activities. In 2014, for the first time, the rate of alluvial on total aggregate production has fallen below the value of 60%. From 2015, whereas statistics are temporarily unavailable, the trend has likely recovered, given works undertaken for the Grand Paris Express (new underground railway ring around Paris) and facilities dedicated to the Summer Olympics 2024.

Increasingly, gravel lakes became more numerous due to quarry closures. In France, their total surface areas amounted to 25 km<sup>2</sup> in 1985 and for the last three decades have increased by a rate of 1 km<sup>2</sup> per year [3]. Owing to aggregate transportation cost on a long distance, many of these lakes were created near cities. Along with the urbanization process, lakes were integrated as paramount elements of urban settings and different functions of cities. Indeed, urban and suburban lakes supply many ecosystem services such as protecting the quality of raw water, enhancing landscape, thriving biodiversity, allowing for fishing and other recreation activities, flood control, coolness island. Notwithstanding the profusion of these surface water bodies and their usefulness to the community, it is worth noting a lack of research in comparison with the extensive research allotted to natural deep big lakes.

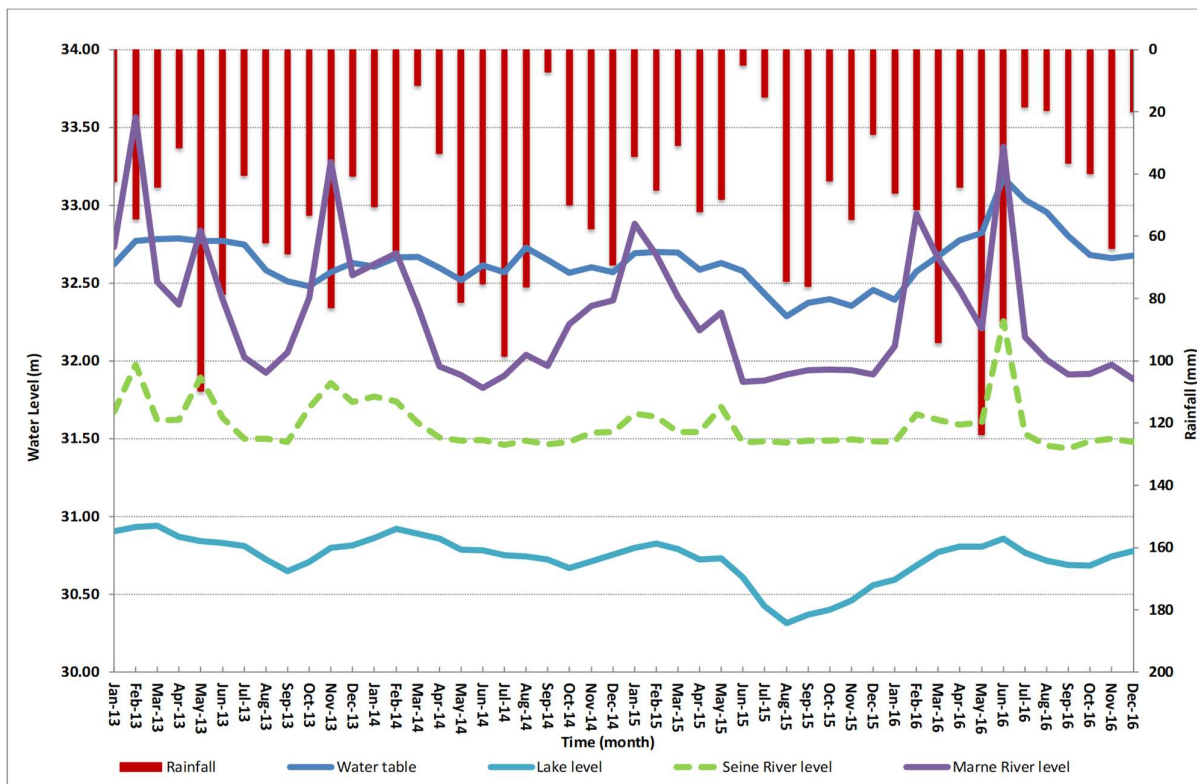
Lakes in general are understood as surface water bodies. However, they are disconnected from the permanent watercourses, unless an exceptional flood occurs. In most of the studies about lakes, direct water transfer between lake and groundwater is given little consideration or none. At best, groundwater contribution is estimated as the residue of the water budget or mass balance [4]. Nevertheless, a gravel pit lake is an “outcrop” of the water table [5]. Within the framework of this study, a request with the keywords « gravel pit lake » in the title has been made throughout literature with a scientific search engine. Among 800 documents found, only 8 examined the issue of gravel pit lake in connection with groundwater. Therefore, the role of this factor is less understood in the hydrology and ecology of these lakes.

### 3. METHODOLOGY

The initial aim was to evaluate interactions of groundwater flow with underground structures (sheet piles, foundations) along the banks of the lake. In order to achieve this “simple” objective, a methodology has been drawn up. The stratified aquifer model has been built from the geological maps and borehole data with the geological data modelling tool GDM (by BRGM). The geotechnical structures have been georeferenced from archived paper cross-sections and maps from the 1970s to 2010s and represented together with the geological interfaces in a 3D GIS (by ArcGIS).

Then, computation of groundwater hydrodynamics is based on finite element modelling (FEM) with the help of FeFlow software (by DHI). Geological data around Créteil lake are logs from 228 boreholes and a mosaic of 4 printed maps with different standards, sourced from InfoTerre, database and web application of the French geological survey (BRGM). Topographical data are twofold: manual bathymetry within and at the contour of the lake and 1 meter-digital elevation model from IGN, database of the French geographical survey.

Hydrological data (Figure 2) are mainly from 2 limnimeters on each of two rivers, records of rainfall measured and interpreted by MétéoFrance from radar and rain gauges, 15 piezometers monitored by DSEA (Sanitation and Environment Services Directorate, Val-de-Marne General Council) monthly for the period 2013-2016, and other water table measurements by RATP (Autonomous Operator of Parisian Transports – a state-owned public transport operator) and SGP (*Société du Grand Paris*, main public operator of the Greater Paris Express subway project).



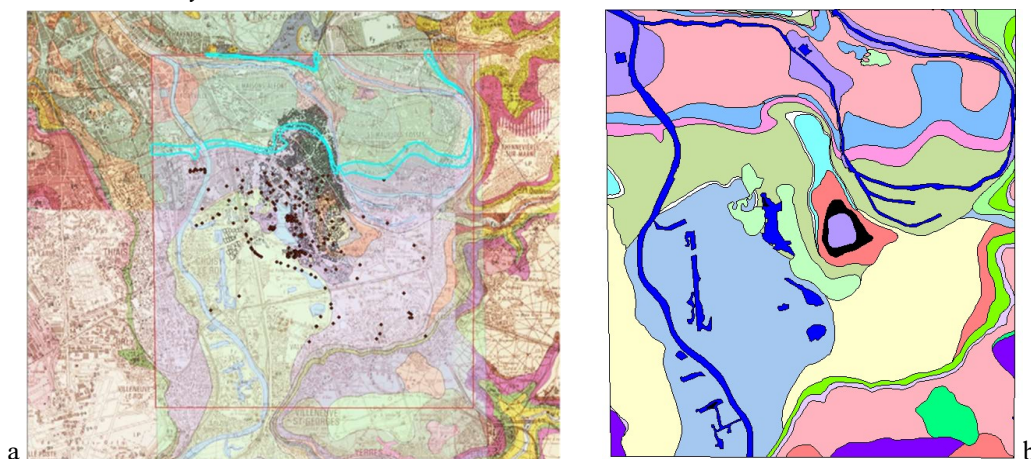
**Figure 2:** Variations of the mean water table (average of level variations in 15 piezometers scattered in the study area as displayed by Figure 7), Seine River, Marne River and Créteil lake levels, for 48 months (2013-2016).

Is the lake level correlated to rainfall or to the water table? Figure 2 displays the average level for the 15 piezometers located around Créteil Lake and southwards. For each river, the level displayed is the average of two limnimetric stations, one upstream and the other downstream of the lake. Variations of water table and lake level for 48 months (2013-2016) show that the lake level is in harmony only with the piezometers and the rivers, not correlated with rainfall unless a time-gap of 10 weeks would be considered. These levels only demonstrate a global tendency in the hydrosystem and no conclusion can be drawn about the flux directions between different water bodies. Hydrodynamic groundwater modelling is necessary to understand the system.

### 3.1 From a geological model to a 3D GIS

The study domain lies in the Paris Basin, at the regional transition area of the Champigny formation related to Bartonian paleogeography between gypsum facies (North-West of the area) and limestone facies (South-East). Substratum of the floodplain includes some remnants (a few meters thick) of this geological formation which is still observable only in the *Mont-Mesly* butte and at the slope of the *Bois de la Grange* plateau at the southward limit of the study area. The Champigny formation is part of a multi-layered phreatic aquifer including alluviums and fills. This aquifer is separated from another one below by a thin aquiclude, a clay horizon inside the Beauchamp formation.

At first, the mosaic of 4 printed maps has been harmonized and vectorized (BRGM) and the domain of study has been extracted: they are superimposed on Figure 3a. Then, this unified map was integrated in GDM software, which is not direct: on Figure 3b, anomalies due to polygons included in other polygons are displayed in black, for instance an island at the North-West end of the Créteil lake or a ring-shape outcrop of clays under the top of the *Mont-Mesly* butte.

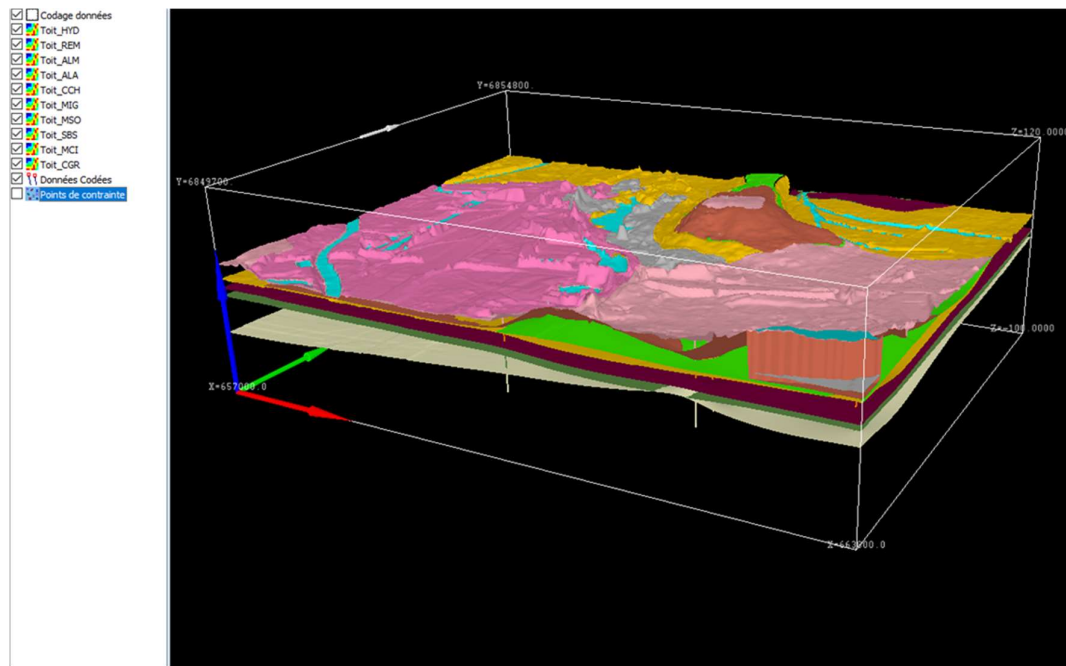


**Figure 3:** The harmonized and vectorized geology of the study area here superposed on the 4 printed maps (1/50 000) and 228 available boreholes (dots) with selection of the study area. **a.** Selection of mid- and upper Beauchamp sand formation (contours in sky blue; the same is coloured in pink on 3B). **b.** The harmonised geological map of the study area: modern alluvium in blue (SW from the lake) and ancient alluvium in yellow (SE from lake). InfoTerre © BRGM.

As the first step of the conceptual geological model, a stratigraphic pile or reference log was defined. It is made of a sequence of relevant “layers” that were chosen from hydrogeological expertise, based on the documents and data compilation. On this basis, the objects that need to be identified in each borehole log and to be represented in 3D will be the interpolated interfaces between the layers of the stratigraphic pile. The geological database is made of two tables: one table for the boreholes (coordinates x, y, z) and one table of lithological layers described in the logs (reference of the borehole, ultimate depth, lithology, description, codification, attribution of an identification number to each layer in the stratigraphic pile). From these two tables are designed the SQL requests, which allow the geological data modeller (software GDM) to connect itself to the database and integrate the bottom (wall) altitude of each layer.

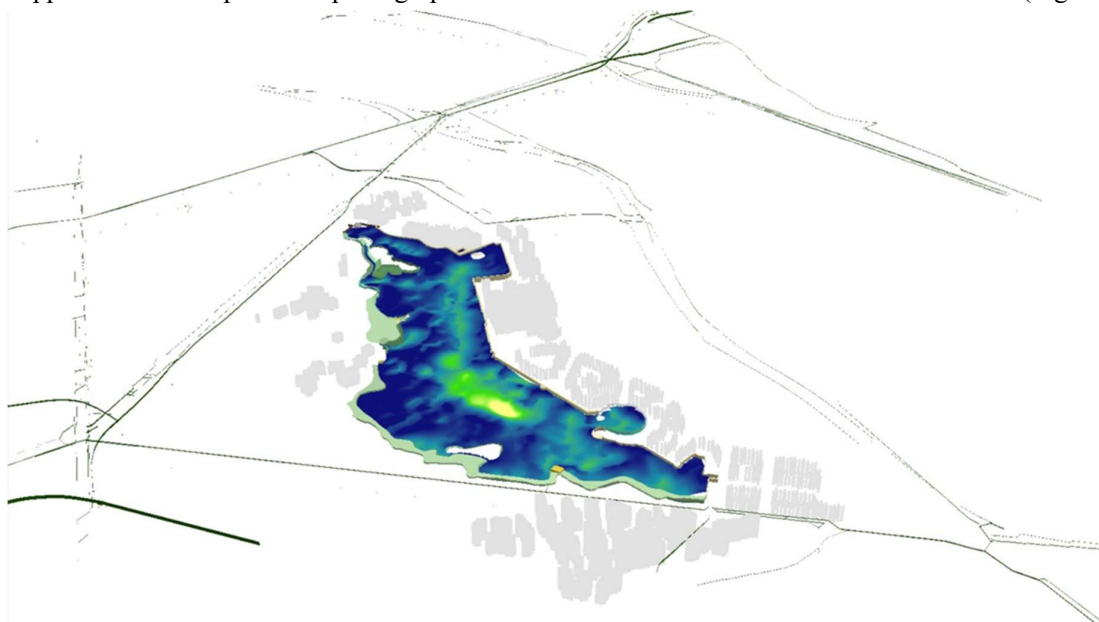
The layers are elaborated thanks to interpolation of their mutual interfaces (linear kriging), processed by conceptual rules (of superposition, erosion surfaces, local heterogeneity), and added up, one after another. When interpolating one interface between two layers, inequality constraints with the next interface are to be considered due to layer thickness variation and local singularities of an interface. The top cap of the geological model (Figure 4) is designed as the topography according to the bathymetric model of the lake ground built from an exponential variogram and from the 1 m digital terrain model (DTM). The positioning error in elevation between the borehole heads and the DTM is then studied. It is supposed that the differences rely on the fills around the boreholes (excavation or aggradation). The fills layer thickness thus varies with time over decades. It does not affect the representation of underground layers.

Then, the interfaces of the geological model (GDM) are imported into the GIS. This task raises some interoperability problems between systems and need to handle different accuracies of positioning in relation to the geographic or geodetic coordinates.



**Figure 4:** A 3D view of the geological model from South-East. Selected area almost same as Figure 1. GDM © BRGM.

Lake banks are modelled in a deterministic way based on archived documents, plans and sections of infrastructures. Especially for the banks set up such as a boat mooring facility and retaining walls in reinforced soil, modelling is designed from digitalisation of the original plans (dated from 1971), bank surfaces and lake ground within 10 meters from the banks. Reduced sheet piles are designed along the docks, 4.5m high, causing a vertical setback with main 7.5 m high sheet piles. This difference in elevation was done during the stabilisation of the lake banks for fitting to the slight ground rise in this area. To give an order of magnitude, the whole lake shores occupy 28,000 m<sup>2</sup>, shared between 21,000 m<sup>2</sup> of topsoil, 4,800 m<sup>2</sup> of steel (sheet piles), 800 m<sup>2</sup> of concrete and 700 m<sup>2</sup> of riprap. Documents on urban planning, interviews with architects, deduction from the typology of buildings, all enabled diameter and depth of foundations (reinforced concrete piles) to be assigned to buildings which form the housings and service activities in a 200 m perimeter around the lake. A total of 4,464 piles of foundations were inventoried and underground car parks were identified, that were mapped with the help of orthophotographs and inserted into the GIS with the sewer network (Figure 5).



**Figure 5:** GIS 3D view from South: the lake bathymetry, different types of banks and foundations. ArcScene © ESRI.

### 3.2 Hydrodynamic finite element modelling

The 3D model geometry was built with FeFlow following the methodology by [6], in a study domain of area 80 km<sup>2</sup> where the ceiling is DEM and the geological model is from non-plane stratigraphic interfaces separating layers of the stratigraphic pile. Automatic meshing of layers is generated by tetrahedrons finite elements (Figure 6a): the size of grid cell varies within 50 – 100 m, adapted to the complexity of the volume.

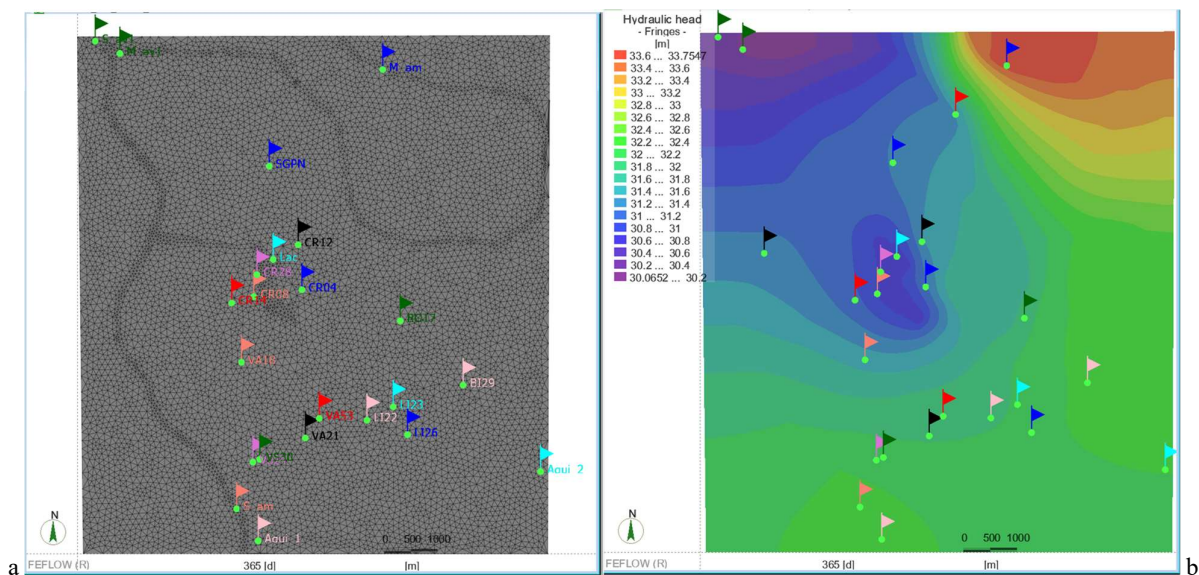
#### 3.2.1 Boundary conditions

The boundary conditions are of three types: fixed head, fixed flux, fixed renewal time at an interface.

Conditions of head applied (x,t-variable) imply the Seine and Marne rivers; moreover, the lake needs a head condition on its contour if  $\phi$ , the frequency of renewal at the interface lake – groundwater, is used as a calibration parameter.

Conditions of flux applied (constant or variable) imply the Champigny formation which contributes an influx into the bottom horizon of the phreatic aquifer along the southern limit of the study area; rainfall is a flux condition uniformly applied. Potential inflow from slope subsurface water in *Mont-Mesly* is not explicit but inlet to the lake from drainage by the stormwater network is.

Condition of renewal at the underground interface with a confined aquifer: frequency of refreshment at the interface of the lake equivalent to the leakage coefficient, known as transfer coefficient in FeFlow software.



**Figure 6:** Same area as Figure 3b. **a.** Meshing the phreatic aquifer of the Marne to Seine confluence. Network of 4 limnimeters, 15 piezometers, 1 piezometer (blue flag isolated) for discussion of the model validity in the northern part, and 2 control points (two flags in sky blue and pink) close to the southward limit of the domain; the latter were computed at the 100 m resolution by the regional model (Aqui'Brie) of the Champigny formation. **b.** Situation in January 2016. The black flag on Seine River westwards from the lake and the red flag on Marne River northwards from *Mont-Mesly* are control key-points of the simulated water table and river levels (inversion points of mutual exchange). Hydraulic head computed by model A in layer 4: here, the *Mont-Mesly* butte and the southern plateau are not inactive since the layer 4 and layers beneath are pre-existing to alluviums and fills. FeFlow © DHI.

#### 3.2.2 Calibration parameters

The objective of calibration is to reproduce hydraulic head in selected piezometers and the lake by comparing simulated (SIM) and observed (OBS) elevations. The calibration was done on water head at 4 wells and lake level history for 4 years (2013-2016).

The calibration parameters are the 3 following: the coefficient of saturated hydraulic conductivity  $K_s$  attributed by layer; the coefficient of effective infiltration that, applied to infiltrated rainfall, gives the recharge per unit area  $R_s$ ; the parameter  $\phi$  frequency of renewal at the interface water table – lake. The model has been calibrated on variations of the lake level (a great number of elements of the mesh are concerned) and the 4 piezometers CR04, CR08, CR28 and VA21. Moreover, 3 piezometers CR12, CR14 and VA18 are at the second rank of quality on the criterium of variations SIM - OBS. The 8 other piezometers will remain useless for any

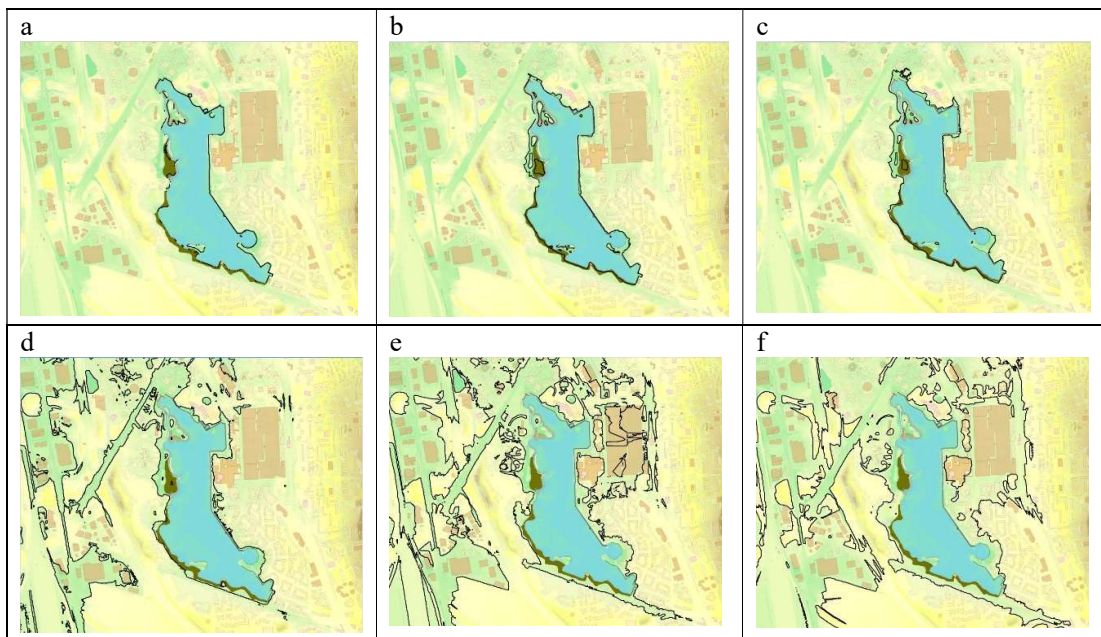
calibration since their variation is very low. In the future, it would be enough to monitor 2 of these 8 piezometers. This analysis will allow optimizing the investment in monitoring in the future.

#### 4. RESULTS

At first, some results come from pure GIS interpretation. A series of maps (Figure 7) show the flood extent by water table rising within the lake, in the theoretical absence of any other influence. To calculate the associated volume of the lake, the limit of extension of the lake surface should be determined for a given elevation of the water table. Using DEM contour lines, it is observed that up to 32 m NGF, the water level produces a polygon that represents the lake's ceiling and allows a calculation of the buffer volume. From 33 m NGF, the lake extends beyond the frame of a single polygon and becomes composed of several zones at the same altitude, some of them isolated, which no longer allows increasing the buffer volume related to the lake.

For the definition of a stratigraphic pile, two cases were considered according to absence or existence of the MIG (marls infra-gypsum) aquiclude. In the selected stratigraphic pile, the main multilayer phreatic aquifer is superposed with another aquifer, confined under a clay horizon within the Beauchamp formation. In the borehole database, most of the total aquifer thickness data is almost uniformly distributed in the 4 to 20 m interval around mean value of 12 m. Then, decreasing distribution is observed from 20 to 50 m. Some rare data was found greater than 30 m. The number of values less than 4 m is not significant. Note that the layer thickness is not modelled as such, it is only the difference of elevation between two interpolated interfaces.

In a 3D view of the geological model built with the interfaces of geological formations, a dilatation coefficient  $\times 10$  is used to valorise the volumes.



**Figure 7.** Flood maps around Crêteil Lake as an effect of groundwater rising: **a to f**, isolines of water elevation, from 31 to 36 meters NGF (national reference to sea level). From **d**, the impact is obvious at the surface. ArcGIS Pro © ESRI.

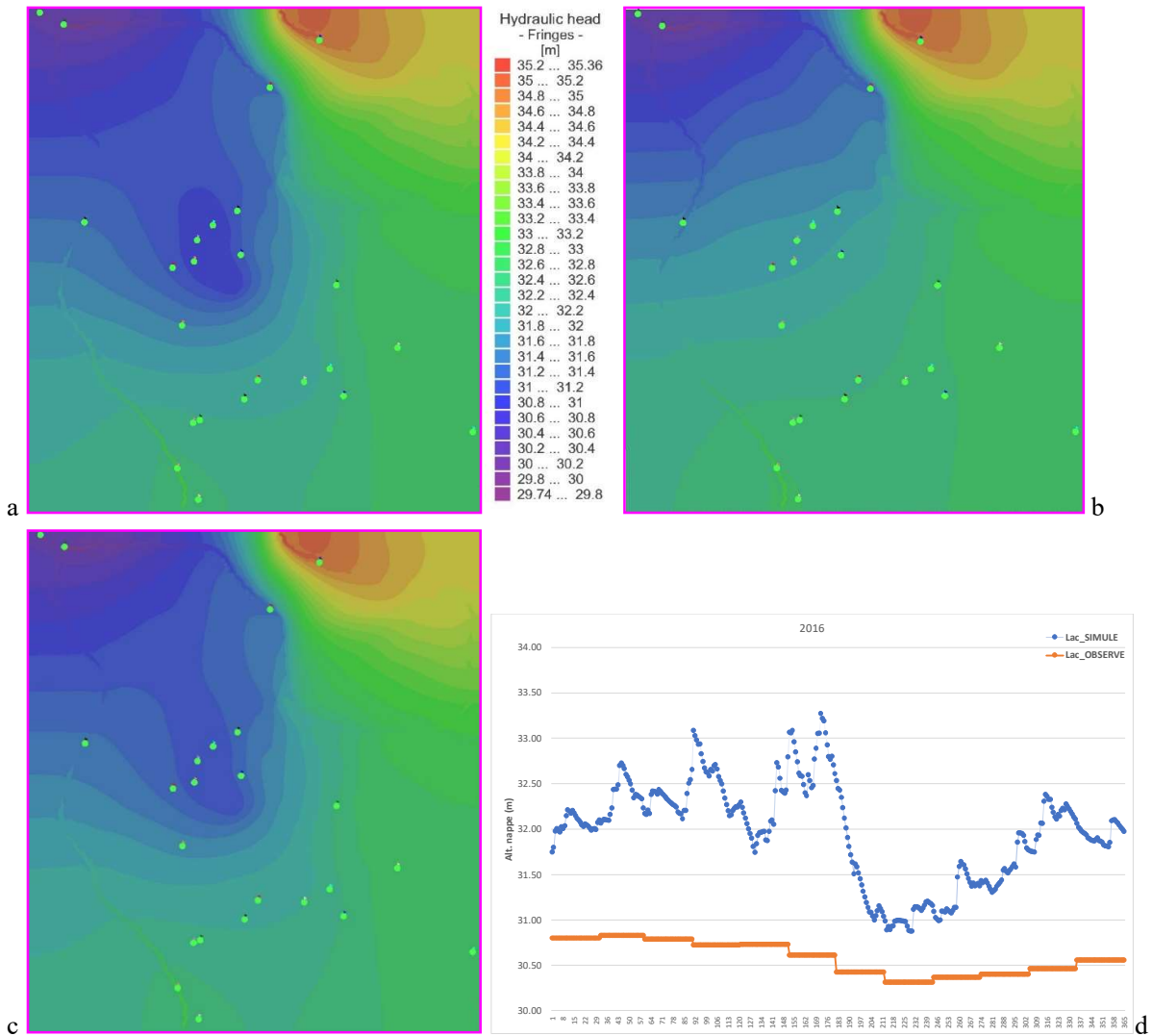
The built 3D GIS will allow studying the intersection between layers and underground infrastructures, especially the foundations. From now, it is possible to see which layer each building leans on, what is a probable thickness of each layer of the conceptual model under the building, and even provide a geological log simulated for each foundation pillar or wall. The hydraulic load curves against a foundation element, pillar or a diaphragm wall, will be deduced from the piezometric level and local gradient. These two pieces of information, and the local flux direction, will be provided by the hydrogeological model.

Until now, only a far-field hydrodynamic model has been developed. Executing the 3D calibrated model produce video showing the daily or monthly evolution of maps such as those at Figure 6b or bloc-diagrams. To simplify the display, the hill of *Mont-Mesly* East of the lake and the edge of the Brie plateau South of the



lake are not drawn while their top layers do not belong to the aquifer (they are visible on the geological map, Figure 3).

After the first calibration phase (Figure 8a), the simulated water table levels in time were found very close (less than 10 cm gap) to the observed levels at 5 piezometers. The rest of monitored piezometers and some control points available from other data providers were also used to validate the simulation with such a good result, on a few months to one-year intervals. This model is further referred to as model A. The second method of calibration (Figure 8c) was effectuated with the help of the parameter  $\phi$  which is the inverse of transfer time throughout the 50 – 100 m-wide border zone. It is the third parameter of calibration, after  $K_s$  and  $R_s$ . The observed head  $h(t)$  in the lake is imposed as a condition, then the parameter of renewal  $\phi$  controls the flux at the interface lake – groundwater.



**Figure 8:** Same area as Figure 3b. Situation simulated in October 2016 for a, b, c, with same hydraulic head scale. **a.** The geological model is excavated for a 3D volume equal to the real gravel pit lake, with “infinite” conductivity attributed to this volume: this model A is calibrated in time with 4 limnimeters + 5 piezometers + lake level (head fixed on the whole lake area, not explicit on the display frame unless the head interval is < 0.05 m). **b.** The lake-calibrated model A is freed from water table constraints (piezo + lake), only the 4 limnimeters keep being honoured, and the excavation is refilled with the geological layers; this model B stands for the past situation without lake. **c.** The lake-calibrated model A is further calibrated based on the parameter ( $\phi$ ) responsible for a transfer rate boundary condition along the contour of the lake, which gives model C fully constrained. **d.** Simulated level at the northern tip of the refilled lake (blue) from model B versus observed level of the actual lake. FeFlow © DHI.

By using this parameter  $\phi$  within a transfer rate boundary condition all around the lake, based on the calibrated model **A**, the  $\phi$ -calibrated model **C** did not provide any improvement of calibration than model **A** at the same points and has been abandoned in the process of modelling as no significant difference can be detected with model **A**. However, this method may be used in a scenario to test for porosity plugging around the lake and for any obstacle to the renewal of water through a border zone. At this stage, it is not known nor assumed that such a plugged porosity zone of width 50 – 100 m exists on some edges around the lake. In the future, a close-field model is envisaged, then the width of the potential plugged border zone may be reduced to 5-10 m.

A scenario with inserting underground structures in the model was simulated to test for a potential dam effect. Sheet piles are continuous tight objects: a condition of zero flow is fixed. Piles of foundations are discontinuous objects: lower  $K_s$  is prescribed. Unfortunately, it did not have significant effect on simulations at the piezometers. No significant difference can be detected with model **A**: these structures do not affect the behaviour of lake at this scale.

A scenario of submersion was tested: the coefficient of effective infiltration to the water table was doubled without modifying the levels of the rivers. That means twice the value of recharge which was taken for the reference model **A**. Comparison with simulation of model **A** has been done at piezometers. This scenario does not influence the lake level nor close piezometers (for instance CR28, the closest to lake with good simulation). With contrast, the water table in the southern area (VA21: 1.2 km South of the lake) is strongly influenced by the increase of recharge.

The calibrated + freed model **B** is a specific scenario without lake (Figure 8b) based on the calibrated model **A**; model **B** stands for a restored state without lake and only constrained by the far-field boundary conditions (rivers and southern inward flux). It may be used itself for transient scenarios with departure from this “free” state.

The simulated hydraulic load values in model **A** or **C** show that the lake promotes leakage between two aquifers (phreatic aquifer and confined aquifer of the Lutetian geological formations).

As mentioned, the model **C**, calibrated by fitting the renewal parameter  $\phi$ , gives results almost the same as model **A**. So, the obtained  $\phi$  can be considered as a global characteristic of the system and applied in other computations:  $\phi = 0.2$  (day<sup>-1</sup>). Then, we estimate the annual flow rate convergent towards the lake through an iso-head surface located at 200 m of the shore:

$$Q = \phi \cdot \Delta h \cdot e \cdot P \quad (1)$$

where:  $\Delta h$  is the mean hydraulic gradient orthogonal to an iso-head line (which delineates the lake),  $P$  is the perimeter of this iso-head line,  $e$  denotes the active thickness of aquifer in the zone of computation.

Equation (1) provides:  $Q = 0.2 \times 0.21 \times 16 \times 5031 \Rightarrow Q = 3,380 \text{ m}^3/\text{day}$ ;  $Q_{\text{yr}} = Q \times 365 = 1,233,915 \text{ m}^3$ . It is likely exaggerated as the active thickness was overvalued.

The overall flow direction is to northwest, towards the confluence point Marne/Seine. The inversion point on the Seine is the point where the exchange flow between Seine River and the phreatic aquifer changes direction as the head gradient becomes opposite. Presence of the lake deforms the equipotential lines in the aquifer differently according to season by moving the inversion point along the Seine, upstream or downstream from a reference point. Thus, in January and July, the Seine is lower than the water table downstream from a point near the black flag (close to the West limit on Figure 6b; see Figure 8). In April, the inversion point is localised about 2 km upstream of the black flag, and in October, it is 2 km downstream of the black flag.

## 5. DISCUSSION

Throughout the literature, the typology of lakes appeared complex. An interesting analogy may be made with the Florida lakes that form in karstic context such as the Lucerne Lake [7]: the low conductivity of the layer under the wall (aquiclude) of the phreatic aquifer makes possible significant if slow leakage at the bottom of the lake through a funnel into underneath limestones of the Upper Floridan formation.

Among practical implications for partners of this study, our approach may bring assistance to consultants. For instance, in the scope of application for an authorization to operate a new incinerator for domestic wastes. We received a request for computation of the flux convergent towards the lake and the period of volume refreshment. The projected facility is located near Créteil Lake and the interdepartmental sports park. Based on the projected atmospheric emissions of this facility, a consultant will estimate the dispersion of pollution, then atmospheric fall-out which is likely to accumulate in the water bodies, the degree of accumulation being dependent on the renewal of water in these lakes. The estimated yearly inflow volume, while probably

exaggerated, is very close to the total volume of water in the lake (1,213,228 m<sup>3</sup>) estimated by the 3D GIS which is probably itself exaggerated as siltation since 2001 was not considered. If the whole influx through the iso-head surface located at 200 m of the lake shore would reach to the lake, then the renewal time of the lake should be 1 year. It is twice longer than previously estimated in past studies, for instance 6 months due to annual flux through the lake estimated at 2,600,000 m<sup>3</sup> by [8].

The main discussion is on the flood hazard in this urbanised part of the Seine River floodplain: 3 stages of the problematic may be considered.

1. In the absence of a retention basin that has been planned in the 1970s but never realised, the lake could serve as a buffer reservoir if it were the outlet of a rainwater collecting network. Indeed, the buffering capacity of the lake is important when compared to conventional basins. Nevertheless, under an exceptional rain event scenario, the lake would be filled quickly. According to the GIS, there would be about 10,000 m<sup>3</sup> of capacity per 10 cm of additional elevation of the lake level. We have seen that the lake can rise to 32 m without overflowing, which makes a maximum possible tidal range of 1.2 m so about 120,000 m<sup>3</sup> storable (i.e. 10% of its current volume). To this capacity would be added a 500 L/s discharge rate evacuated to the Seine River by the stormwater network, which would be useful for a few weeks. In this scenario, it would be interesting to study the influence of the high lake level on the piezometric variation of the water table around the lake and to identify areas where the water table may rise and affect building foundations or underground car parks.

2. In a scenario of exceptional high level of the Seine or the Marne or both, without flooding of the study area, it will be possible to simulate influence of the level of both rivers on the water table variation and consequently on the lake level. A lake level forecast system based on rainfall scenarios and Seine and Marne river levels would inform the public a few days in advance for noticeable variation of the lake level.

3. In case of flooding of the lake area by a Seine River overflow, what would be the role of the lake, would it facilitate the return to normal state? Yes, it is a natural outlet to the Lutetian aquifer, which is the largest buffer that can be dreamt of, if it is not itself in overcharge before the event. But no methodology is available now to calculate the instantaneous leakage rate at the bottom of the lake to the Lutetian aquifer.

## 6. CONCLUSION

The first conclusion we draw from the results of the far-field model is a conceptual one: Créteil Lake is not a cross lake as previously thought [9] but rather a terminal lake... however with vertical leakage through the lake bottom which allows for a connection with a deeper, likely confined aquifer (Lutetian) which did not exist in the 1970s. As the second conclusion, the renewal period of the lake is one year.

Renewal of the lake water volume is almost fully by groundwater and natural flow between two aquifers: at the scale considered, it is not impeded significantly by inflow from the stormwater network of *Mont-Mesly* while it is accounted in the model. Also, there is no contribution of the sewers connected to the Seine River to regulate the lake level. The consequence for water managers is that there is no need to invoke any intervention as rainwater drainage management. Moreover, at the scale considered, no influence of geotechnical structures such as foundations could be proved with the far-field model.

Further work will imply a close-field hydrodynamic model within 500 m around the lake at the 5 meters resolution to better consider a potential influence of underground structures at metric scale. Boundary conditions will be applied from the simulation results of the far-field model **A**; however, these conditions will be complex in space and time... and the external boundary surface is not defined yet. Also, one high resolution bathymetry survey of the lake will be performed in order to localize the deepest point of the lake more accurately, then to describe the morphology of this "hole". Indeed, this hole formed by dissolution of gypsum for decades and is likely to continue evolving and increasing. Another related need is to estimate the rate of sedimentation for the period 2012 to 2018 on the lake ground and within the hole. Moreover, exploration by a professional dive-crew in zones of interest such as the deepest part of the pit is planned.

In conclusion concerning water table rising hazard management in the floodplain of the Seine and Marne rivers, the evacuation of water of the phreatic aquifer would pose an acute difficulty if intense rains were to occur on the confluence area whereas the levels of the Marne and Seine rivers were already high at the same time, concomitantly with a high level of charge in the confined Lutetian aquifer. The latter may go under an excess of load inherited from older rainfalls (10 weeks before) on its feeding outcrops. Consequently, a local flood that would occur by a rise of water table and an overflow of the lake might affect the city centre, the prefecture of Val-de-Marne department, that is to say, the centre of crisis management, plus the regional shopping centre, the regional wastewater treatment plant and vital traffic routes.

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