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Reconstruction and simplification of the Greater Paris sewerage network

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KEYWORDS

Sewerage network reconstruction, artificial and natural networks connection, urban water flows, combined and separate sewerage systems

ABBREVIATIONS

| | |
|-------------|--|
| CNRM | French Research Meteorology Center |
| CNRS | French Research Center |
| CSO | Combine Sewer Overflow |
| LEE | Water and environment research laboratory |
| MAV | WWTP on the Marne river (upstream) |
| NBS | Nature based solutions |
| PIREN-Seine | French Research program for the study of the Seine basin |
| SAM | WWTP on the Seine river (upstream) |
| SAV | WWTP on the Seine river (downstream) |
| SIAAP | Greater Paris sanitation authority |
| TEB | Town Energy Balance scheme |
| TEB-Hydro | urban water balance module from TEB |
| TOHR | TOol for Hydrographic network Reconstruction |
| WWTP | Waste water treatment plant |

ABSTRACT

In order to mitigate negative urbanization effects on urban water management, nature based solutions (NBS) are often recommended. Some of them can also be recommended to improve thermal comfort, inhabitants well-being, their security, ... They can also take part in climate change adaptation strategies. A more systemic evaluation of such solutions is then becoming essential. The hydro-climatic model TEB-Hydro has been developed in order to evaluate urban planning projects, regarding urban water management and thermal comfort, at the City scale.

TEB-Hydro model, based on a regular mesh grid, needs to know the water different paths (at the surface, inside the stormwater or combined network, into the ground.). An automatic tool (TOHR) has been developed, from urban data banks, to build an oriented graph of the different water flows, that is then projected on TEB-Hydro grid, to provide to the model all the parameters needed for routing calculation. This oriented graph is based on the stormwater, waste water, combined and natural networks. Thus, it allows the reconstruction of a complete network, by taking into account all the different water flows. Nonetheless, this rebuilt network has to be simplified, in order to be adapted to the grid spatial resolution.

The reconstruction result, at the Greater Paris scale is globally satisfying. Numerous errors are due to wrong connections, but at a fine scale. The flow path is then a bit longer than in the reality. The larger difficulties are over Paris where the network is a crossroad with numerous meshes. The reconstruction of the separate system is better as it is less meshed than the combined one. And even on the combined system, realistic large drained areas defined at different points on the network are obtained. Then the reconstructed network is available for hydrologic simulations.

1 INTRODUCTION

World urban population has been growing for several decades and is expected to continue to do so in the coming decades (United Nations, 2018). Urbanization is accompanied by the waterproofing of surfaces and the modification of water flow paths (sewerage networks, closure of urban rivers) (Leopold, 1968). Thus, the water cycle is strongly modified (Fletcher et al., 2013). The infiltration of rainwater into the soil is greatly reduced, leading to an increase in surface runoff. Evapotranspiration is also lower. The flow of water, concentrated in the sewerage network collectors, is accelerated. The run-off water leaks out surfaces potentially polluted by human activities (traffic, industrial activities, etc.) and the materials used (zinc, lead, soot, etc.). This water can be treated by wastewater treatment plants (WWTPs), in the case of low rainfall and a combined sewerage system, or discharged into the natural environment, in the case of a separate network or more or less heavy rainfall in a combined sewerage system (via combine sewer overflow). In urban areas, floods are then more frequent and more intense than in rural areas, and the quality of river water can be seriously degraded.

The water Law (2000/60/EC) obliges communities to maintain good ecological status of the waters. In particular, discharges to the natural environment must be limited. Solutions exist to limit these discharges. They aim to favour water management at source, with the help of the so-called alternative techniques. These alternative techniques aim to bring the urban water cycle closer to the natural water cycle by facilitating the infiltration of water into the ground (*i.e.* rain garden) or surface storage before infiltration (*i.e.* swales) or discharge into the network (*i.e.* greenroofs). These solutions fundamentally change urban water management. Indeed, communities manage their network using information on rainfall, wastewater production, detailed representation of flows within the network and possibly the height in rivers receiving discharges. The increasingly widespread dissemination of the alternative techniques now implies taking into account possible interactions with the soil. The tools currently available to managers are not able to realistically represent these processes.

The PIREN-Seine project, phase VII, has, among other objectives, to assess the impact of urban areas on the Seine, in terms of pollution and hydro-geological functioning, in particular the urban zone made of City of Paris and the three departments (Val de Marne, Hauts-de-Seine and Seine-Saint-Denis) that it will be improperly named Grand Paris. A tool capable of representing the different processes involved in the water cycle, as well as the different flow paths is needed. The LEE (University Gustave Eiffel), in collaboration with the CNRM (Météo-France, CNRS) has developed

such a tool (TEB-Hydro) (Stavropoulos-Laffaille et al, 2018). Its aim is to work on an annual and territorial scale, in order to simulate the "great water cycle" and to characterize its possible evolution, depending on the evolution of urbanisation, developments with alternative techniques or climate change. At such spatial and temporal scales, the simplification of space is a prerequisite. The TEB-Hydro hydrological model segments the space using a regular mesh grid, according to a resolution to be determined according to the site studied. In order to maintain consistency between the processes but also to limit calculation times, the very dense sewer network, needs to be simplified, but with an equivalent functionality. This tool is obviously not intended to replace the current sewerage network management tools, but to complement them. It is not a day-to-day management tool, but a decision support tool for the evaluation of development projects.

Within the framework of the PIREN-Seine project, the objective was therefore to define the modelling framework, on the urban area centered on Paris, by delimiting the area to be studied, by collecting land use and meteorological forcing data, necessary for the model. The first step was to understand the functioning of the sewerage network on the scale of the studied territory, before reconstructing it by simplifying it, according to the resolution of the TEB-Hydro hydrological model. In the methods part, TOHR is presented as well the studied area and the sewer network functioning. In the results part, the reconstruction of the network is presented before being evaluated and discussed.

2 METHODS

2.1 Studied area

The studied area has been delimited according to the scale at which the sewerage network is managed over Paris (France capital) and its suburbs. The SIAAP (Syndicat interdépartemental pour l'Assainissement de l'Agglomération Parisienne) covers four departments: Paris, Hauts-de-Seine, Seine-Saint-Denis and Val de Marne. 180 municipalities from the bordering departments have signed an agreement to be included (Figure 1). In order to simplify the data collect and our discussions with the management services, it has been decided to limit the study area to only the four departments.

The area is then composed of 124 municipalities covering an area of 762 km² (Sénat, 2017). It is a very dense area with 20 569 inhabitants/km² for Paris, 8 724 inhab./km², 6 287 inhab./km² and 5 277 inhab./km² respectively for Hauts-de-Seine, Seine-Saint-Denis and Val-de-Marne departments. The area is covered by 84.5% of urbanised areas, characterized mainly by collective housing into Paris and a mix between collective and individual housing in the suburbs. The non-urbanized areas consist of natural, agricultural and woodland areas.

The climate is altered oceanic with a yearly mean temperature ranging from 8.9°C to 16°C (1891-2010) and yearly mean rainfall equal to 637mm (1981-2010) (<http://www.meteofrance.com/climat/france/paris/75114001/normales>).

The study area is localized inside the Seine basin and is crossed by two of its tributaries: La Marne and L'Oise. Three canalized watercourses are present in Seine-Saint-Denis (La vieille Mer and La Morée) and Hauts-de-Seine (La Bièvre).

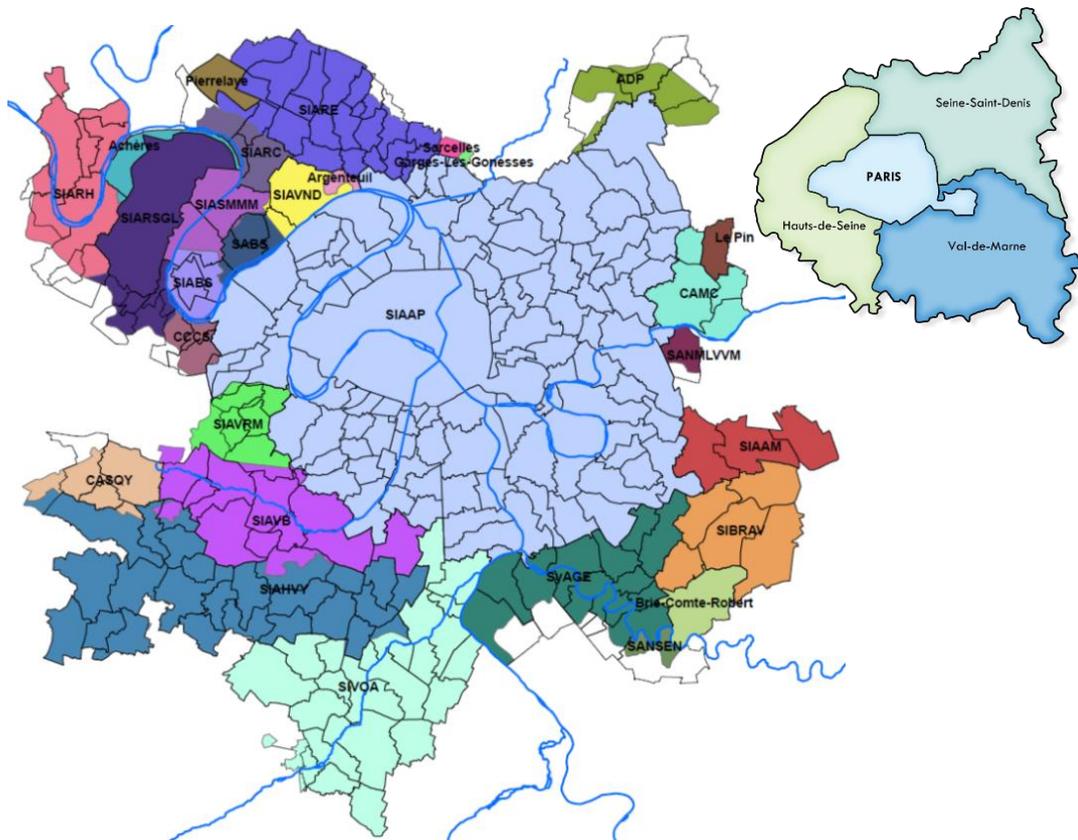


Figure 1 SIAAP area (Tabuchi and Penouel, 2014). On the top-right corner, The City of Paris and the three departments are localized (<https://commons.wikimedia.org/w/index.php?curid=2133888>).

The sewerage network (Lotfi et al, 2016a) is organized according to three levels: the territorial networks collect and transfer the effluents only to the departmental networks, managed and owned by the departments. The departmental networks have only a role of transfer of effluents to the interdepartmental network. This one transfers the effluents to the waste water treatment plants. The study area is composed of 6 main WWTP (Figure 2). The oldest one Seine aval (SAV) has the largest treatment capacity (60% of the waste water from SIAAP area). Seine amont (SAM), the second one in treatment capacity, treats the effluents from Val de Marne, Bièvre valley, the southern part of Hauts-de-Seine and Seine-Saint-Denis. Marne Aval (MAV) is a smaller WWTP, treating the effluents from the southern part of Seine-Saint-Denis. Seine Grésillon is outside the study area, and Seine Centre (SEC) and Seine Morée (open in mid 2014) have been estimated with a so small capacity, that they have been neglected. Thus, Paris, Hauts-de-Seine (except the south part), Seine-Saint-Denis (north and western parts) effluents are transferred to SAV, leading to a flow direction mainly from the south-east to the north-west, while Val-de-Marne and the southern parts of Hauts-de-Seine and Seine-Saint-Denis are transferred to SAM and MAV. Then on the low-right corner of the study area, the flow direction is from west to east and from north to south. Some pre-treatment plants are localized upstream of SEC and SAV and several large tanks allow to manage effluents especially during strong rainfall events and maintenance tasks. Lastly, at different points of the network, the effluents can be routed through a longer path to a different WWTP or to the usual one, in order to help the urban water management. In the oldest part of the area, the sewerage network is a combined system, while on the eastern part, the network is a separate system. But there are some areas where both combined and separate systems coexist.

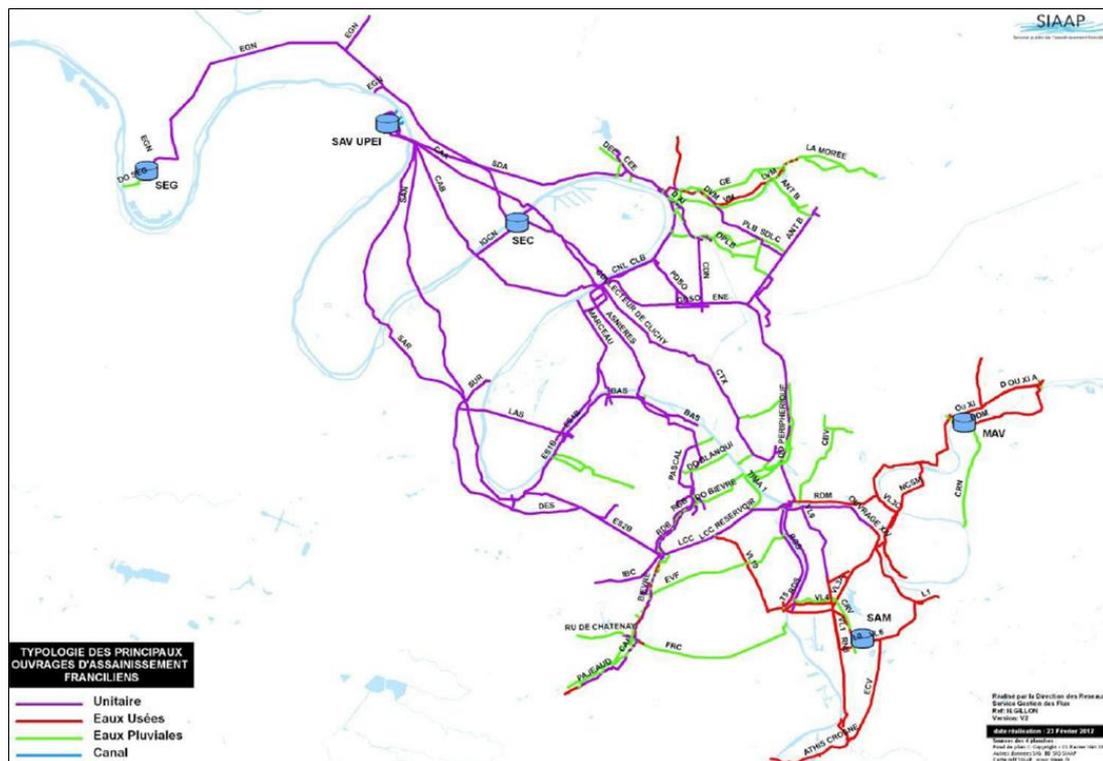


Figure 2 Interdepartmental sewerage network (combined: purple, red: waste water, green: stormwater) and the main waste water treatment plants (SEG: Seine-Grésillon, SAV: Seine aval, SAM: Seine amont, MAV: Marne aval, SEC: Seine Centre) (SIAAP, 2014.)

2.2 The Tool for Hydrographic network Reconstruction (TOHR)

The tool TOHR (Loffi et al., 2016b) has the goal to both build a network with the same functionality as the real one and simplify it, depending on the mesh grid of a hydrological model to which it is dedicated. The first step is then to select the nodes of the resulting oriented graph and in a second step the nodes are connected. The nodes are the “outlets” of the grid meshes. Then, in a mesh, there can be a stormwater node, or a stormwater and a waste water nodes, or a combined node or a waste water node. But it is not possible to select both combined and stormwater nodes as well as combined and waste water nodes, in a same mesh. The user has then to choose the type of network that will be preferred between separate or combined systems by beginning by it. Regardless of the network type, the node in a mesh is selected among all the available manholes by choosing the one with the lowest altitude. Once a node is selected, the mesh is assigned to the type of the sewerage network (separate or combined). In a second step, the CSO and the lift stations are added and have to be connected to the node in the mesh (the lift station on the stormwater network are not yet taken into account). The third step allows to connect the nodes to each other from upstream to downstream, with each node able to have several upstream connections and only one downstream connection. The connection slopes have to be negative except when one of the nodes is linked to a lifting station. The CSO are linked to the node of the same mesh. At such a node, the excess of water (larger that a given threshold discharge) is transferred to the river instead to the downstream node. For the stormwater network the length of the connection must not be more than twice the distance between the node and the nearest river. The waste water and combined nodes are simultaneously connected. The connection length cannot exceed three times the grid resolution. When there is no possibility to connect a node to another one, following the rules, then the connection is made to the nearest one. The resulting oriented graph takes into account the different types of natural and artificial

networks and their connections. The user has to define outlets among the set of nodes (except the CSO that are automatically selected). The last step of the process consists of the projection of the graph on the mesh grid, in order to (i) connect the meshes to each other, depending on the network and (ii) calculate the distance from each mesh to the first outlet, for each type of flow (river, storm water, waste water) and between the outlets. The meshes not crossed by a sewerage network are connected to the other meshes for the surface runoff, depending on the topography by using the D8 method (O'Callaghan & Mark, 1984).

2.3 Application on the study area

The grid on which the reconstruction is based has a resolution of 250m. The domain extends over a 73km x 73km domain, covering the four departments. For spatial resolution reasons and in order to limit the number of contacts, the territorial sewerage network has been ignored, except for Paris where the “departmental level” was not dense enough. First, the interdepartmental network has been reconstructed, and then each department network, by connecting each one to the interdepartmental network (Lotfi et al, 2016b). Finally, a phase of homogenization has been needed, in order to obtain a full hydrographic network. Each sewerage network manager has shared description data of their network: manholes, pipes, CSO and lifting stations, WWTP and their collect area. Depending on the data quality, for some departments, the reconstruction of the network has needed to improve the altitude of the manholes by interpolation along a pipe or by using the natural topography. In Val-de-Marne department, two networks can coexist: one at the surface (the newest one) and one deeper (the oldest one). Regarding the functioning of the network, following discussions with the team managing the network, the deeper network has been excluded. At some points of the network some “meshing” have finally been added: a node is then able to have two downstream paths. This allows a more realistic functioning of the whole network. These meshes function as the CSO: they act from a threshold discharge, but the second downstream pathway is not connected to the river but to another node of the same system type: a stormwater or a combined system.

Table 1 Synthesis of provided observed data with the corresponding time period by each department.

| Department | Time period | Type of data |
|-------------------|------------------------|---|
| Hauts-de-Seine | 2012-2018 | 33 points on combined system, 73 CSO, 18 raingauges |
| Seine-Saint-Denis | 2000-2018 | 4 CSO, 3 points on stormwater network, 7 raingauges |
| Val-de-Marne | 2002-2007 2002-2008 | 11 CSO 31 raingauges |
| Ville de Paris | 2014 | 3 CSO, 30 points on combined system, 14 raingauges |

Before reconstructing the sewerage network with TOHR, the sewerage system functioning has to be well understood. This needs to meet the sewerage system management teams and to carefully study the provided data and documents. The reconstruction has been done several times, as due to the amount of data, there are always wrong data that have not been noticed during the pre-treatment phase. Once a reconstruction without any obvious mistake is available, a new exchange with the sewerage management team is organized, in order to criticize the reconstruction and eventually improve it.

In order to select the outlets over the study area, a lot of data has been provided by the sewerage network management teams over different time periods (Table 1). Given the large amount of data, a two-steps approach has been applied. A first selection among all the stations has been made depending on the upstream network reconstruction quality. Then, depending on the data

availability and quality, only a part of the remaining stations data has been validated. The outlets have finally been selected depending on the data quality and the time periods.

3 RESULTS

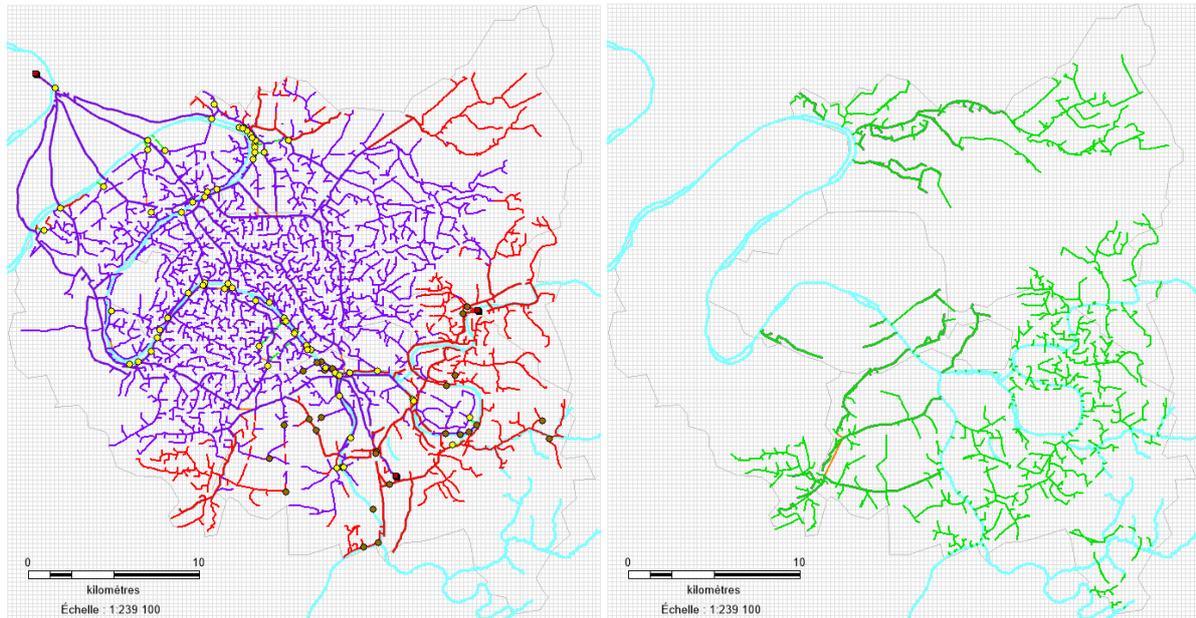


Figure 3 Reconstructed network with TOHR for the interdepartmental (thick line) and the departmental networks (thin line) for the combined (purple) and waste water (red) networks (left) and stormwater (green) networks (right). The combined sewer overflows are in yellow and the lifting stations in brown. The WWTP are in red (square). The hydrographic network is in blue and the grid and the departments delimitations are in light grey.

Table 2 Synthesis of the selected devices for the reconstruction, at the Greater Paris scale.

| Type of devices | Number of selected devices | | |
|--------------------------------------|----------------------------|-------------------|--------------|
| | Total | Interdepartmental | departmental |
| Combined sewer overflows | 66 | 34 | 32 |
| Lifting stations | 33 | 3 | 30 |
| WWTP | 3 | 3 | - |
| Combined meshing | 14 | 11 | 3 |
| Stormwater meshing | 2 | 2 | - |
| Outlets (except CSO and WWTP) | 21 | - | 19 |

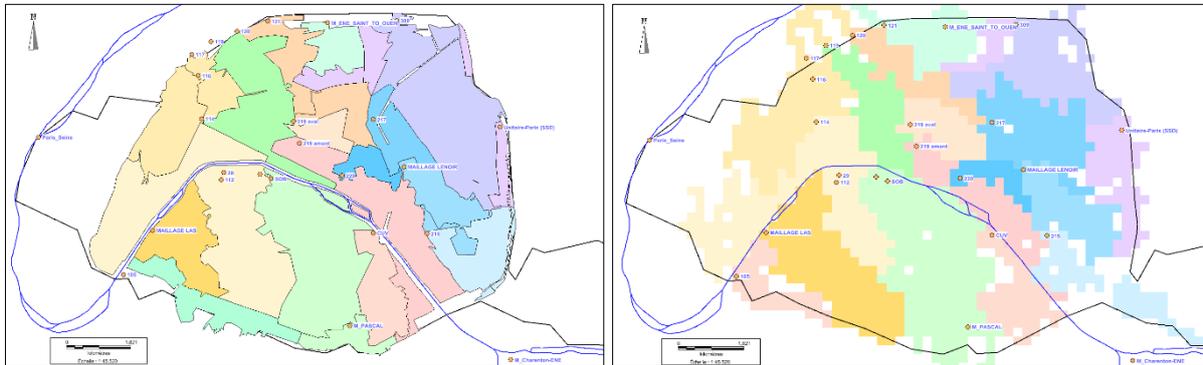


Figure 4 Drained areas by the same 18 points on the real (left) and reconstructed (right) networks over Paris department.

The final and approved reconstructed network is presented in Figure 3 (Chancibault et al, 2019). The synthesis of the selected devices for the reconstruction are listed in Table 2. Globally the reconstruction compares well with the real network: especially the interdepartmental one (due to its low density) and in the areas with separate systems. The more noticeable errors are localized on the eastern and southwestern parts of Paris (Figure 4) on the combined network, probably due to a weak quality of manhole altitude data or a lack of information about any lifting stations in the area.

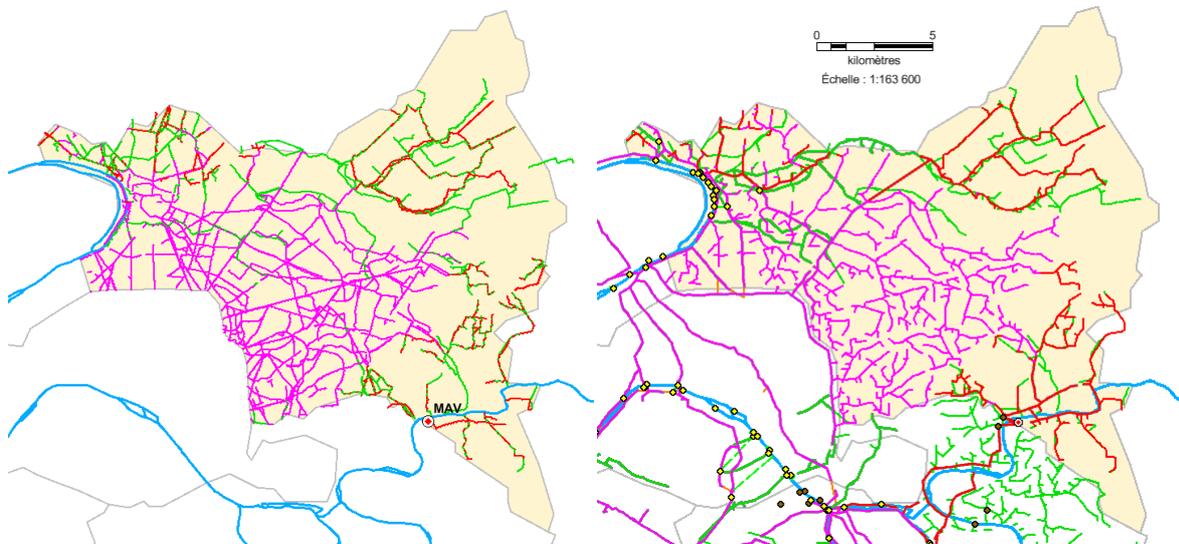


Figure 5 Real (left) and reconstructed (right) Seine-Saint-Denis sewerage network. The departmental (thin line) network is connected to the interdepartmental (thick line) one. The combined (purple), waste water (red) and storm water (green) networks are represented, as well as the combined sewer overflows (yellow), the lifting stations (brown) and the WWTP MAV (red square in a circle). The hydrographic network is in blue.

The drained areas of the network were not available for comparison, for all the departments. The evaluation was then made possible by a simple visual comparison between the real and the reconstructed networks. For example, for the Seine-Saint-Denis network reconstruction (Figure 5) if real and reconstructed networks cannot be totally equal due to the spatial simplification, the comparison is globally satisfying.

After the projection step of the network on the mesh grid, the catchments associated to the selected outlets (Table 2) are visible (Figure 6). Four storm water catchments, three waste water

catchments and eleven combined catchments can be studied and simulated with the hydrological model (Bernard et al, 2020).

The reconstruction of the sewerage network by TOHR enables also a finer analysis of the moving delineation of the drained areas, depending on the rainfall events intensity (or the network maintenance). Figure 6 shows the drained areas when the CSO or the meshes are or not active. Without any overflow, the P117 outlet drains the dark green area (Figure 7 left). With all the CSO in action, the light green areas only partially contribute to P117 outlet, under a threshold water level, above it is transferred to the Seine River. If the meshes are in action, the contributing area is more complex: the drained area by the mesh St Cloud, is partially transferred to P117 catchment whereas when the mesh St Cloud is not in action, its drained area is not included at all in P117 catchment. The activation of SOB029 mesh has the same effect with an extension of P117 drained area. On the contrary, for ESB1 mesh, its drained area is partially subtracted to P117 catchment if it is activated.

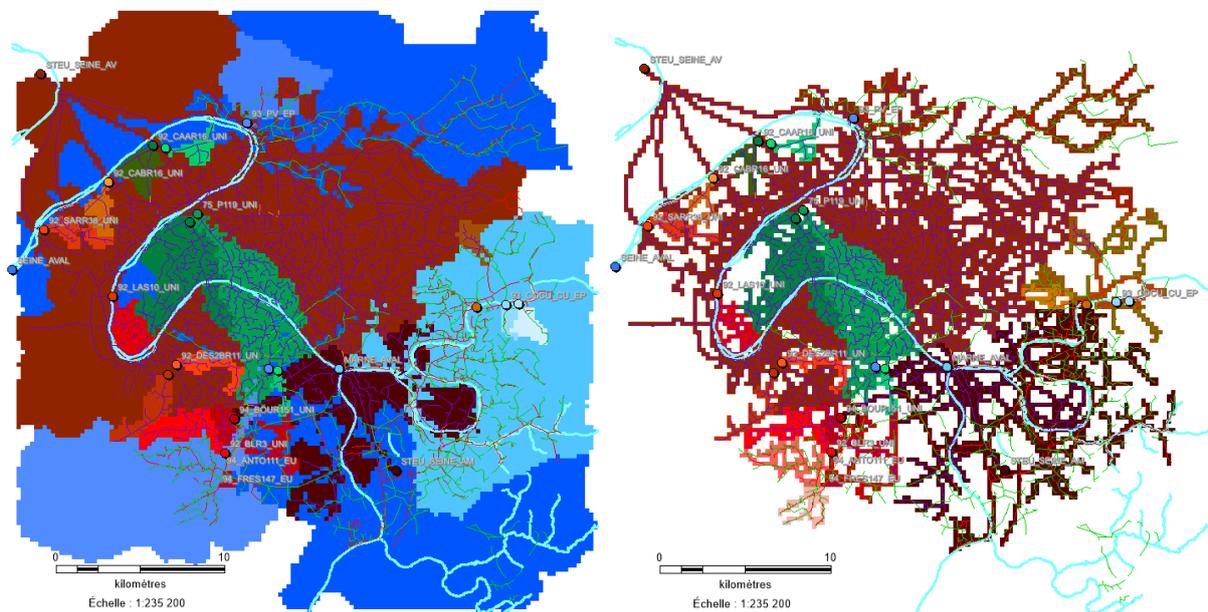


Figure 6 Selected outlets (colored points) and their drained area for stormwater (left) and waste water (right). The color scales for the drained areas correspond to the outlets' one: light blue are for Marne aval catchment and subcatchments and dark blue for Seine aval catchment and subcatchments, along the stormwater and hydrographic networks. The light brown, red and green are for the WWTP SAV (STEU_SEINE_AV) catchment and subcatchments, the dark brown for the WWTP SAM (STEU_SEINE_AM) catchment and the light brown for the WWTP MAV (STEU_MARNE_AV) catchments, along the combined and waste water networks (left and right).

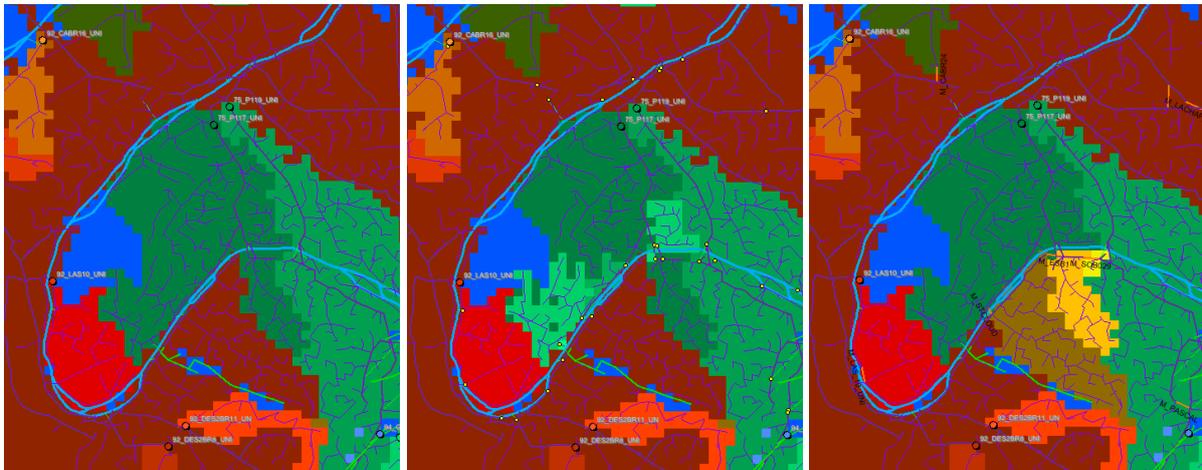


Figure 7 Drained area by the P117 catchment (dark green) without any combined overflow device in action (left) with the combined overflow devices in action and the meshes (right) in action.

Conclusions

In order to provide to the hydro-climate model TEB-Hydro, able to evaluate NBS impacts on urban water management and thermal comfort, all the needed parameters to transfer storm water at the surface, inside the sewerage network and through the ground, an automated tool (TOHR) has been developed. Urban data bases rarely offer a graph of the sewerage network with topologically connected objects. TOHR has then to reconstruct an oriented graph of the sewerage network with all the sewer systems. This graph is also connected to the hydrographic network. Based on the grid mesh of the hydrological model, the graph is simplified (less dense) compared to the real network, but it has to be functional. The projection of the graph on the mesh grid of the hydrological model enables to calculate the parameters needed for the water routing over the domain (distance for each mesh to the direct outlet, type of flow (surface, ground, sewer network, river)).

The study site is the Greater Paris, that is the scale at which the sanitation is globally managed. The departmental level, the second level of sanitation network management has also been investigated, in order to reconstruct a functional network. The territorial level, too dense compared to the spatial resolution of the hydrological model grid has not been included in the reconstruction. Thanks to different meetings with the network management teams, the provided data and shared documents, the functioning of each network (interdepartmental and each departmental ones) has been described. The final reconstruction shows errors mainly on the combined system, that has more meshes than the separative one. Nonetheless, the reconstructed network compares well (visually and by the mean of drained areas) to the real network at both the interdepartmental and departmental levels.

A large amount of hydrological data on both combined and separative systems have been collected, selected, qualified and validated. Several outlets have then been selected allowing the study of different catchments over the domain (combined, waste water and storm water ones). The impact on the contributing areas of CSO and/or meshes activation is easily highlighted with TOHR. Data are now available for a hydrological modelling over the entire area, with TEB-Hydro model (Bernard et al, 2020). For the combined system, the waste water signal has to be extracted, to be compared to the simulated discharges. The final objective is to perform climate change adaptation strategies evaluation.

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