Integrated Smart Water Management of Sanitation System in the Greater Paris Region

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Summary

The greatest challenge that the sanitation system of the greater Paris region had to face in the final decades of the twentieth century was the quality recovery of the Seine and Marne rivers. The pollution of the receiving water was caused by a lack of treatment capacity and technical performance as well as by combined sewer overflows during rain events.

After decades of investments, huge improvements in the water quality of receiving waters were obtained and the objectives of the European Water Framework Directive (WFD) are close to being achieved thanks to the development of wastewater treatment plants and a sewage transport system. At the same time Syndicat Interdépartemental pour l'Assainissement de l'Agglomération Parisienne (SIAAP), the public utility in charge of the transport and treatment of wastewater for the Greater Paris region, has also invested in a real-time control following a 1997 sanitation masterplan study that recommended the implementation of real-time control for better control of stormwater pollution caused by combined sewer overflows, allowing a reduced need for storage facilities.

Building upon existing systems and the experience acquired since the mid-1980s at SIAAP as well as each of the its constitutive *départements*: Paris, Hauts-de-Seine, Seine-Saint-Denis and Val-de-Marne, this real-time control system called MAGES (*Modèle d'Aide à la Gestion des Emissaires du SIAAP)* began operation in 2008. The new system (as described in section 3.2) integrates all the data from each *département* system, and is powered by a hydraulic deterministic model fed in real-time by 2000 sensors. It provides flow forecasts for a trend scenario in each part of SIAAP's networks and at each treatment plant on different time scales depending on the weather conditions. This trend scenario is used by the operators to adjust the management of the system.

This smart system takes advantage of the capacity within the coverage area to transfer sewage from one wastewater treatment plant (WWTP) to another. Such transfers enhance system wide security in case of shutdown due to any reason such as planned works or incidents.
MAGES has been the driver of several changes in the way to see and operate the sanitation system. First, each operating site has the knowledge in real-time of what has happened elsewhere on the sanitation system, resulting in a shared and global view of the system. At the same time, the SIAAP department that operates MAGES has a global overview of the hydraulic running condition of the whole system.

Ten years after the commissioning of MAGES, it is still difficult to assess its benefits in terms of savings either on investment or operation costs. Nonetheless, smart management is here to stay. Projected constraints on the operation of Paris's regional sanitation system from tighter regulations, population growth and effects of climate change on the Seine hydrology are impelling SIAAP to develop smarter tools aimed at reducing pollutant loads discharged into the rivers without entailing excessive costs.

This case study details the development of a real-time control system (MAGES) in the Paris region designed to better control stormwater pollution caused by combined sewer overflows and to optimize the need for additional storage or treatment facilities. The case study is structured to outline the challenges facing the Greater Paris region water and sanitation networks, and the solutions provided by SIAAP, the public utility in charge of the treatment and transport of wastewater, over the past 20 years After a brief overview of the geographical characteristics of the region of concern, it introduces SIAAP and the challenges facing it in ensuring improved quality of the Seine. This is followed by a description of the evolution and features of the MAGES system, links to the Sustainable Development Goals, and challenges and opportunities that lie ahead.

1. Background

To enable better understanding of the general context in which the project takes place, the following section describes the role of SIAAP as an institutional organization, and the geographical situation, climate conditions and demography of the Greater Paris region.

Box 1. Water resources in the Greater Paris region and SIAAP's collection area

Catchment:

Name: Seine basin
Area within Seine basin: 77,000 km^2
Area within Greater Paris region: 2845 km^2
Area within SIAAP's collection area: 1800 km^2
Principle sources of water used: 15-20 % groundwater, 80-85 % from surface water in which 60% from Seine, 30% from Marne, 10% from Oise.

Climate:

Temperate with oceanic influence
Annual Rainfall: 640 mm

Demographics:

Population: Greater Paris region: **10.5 million inhabitants (**SIAAP's collection area: **9 Million inhabitants)**
Population density: Greater Paris region**: 3690 inhabitants/km^2** (SIAAP's collection area: **5000 inhabitants/km^2)**

1.1 Geography, climate and hydrology of the Greater Paris Region

1.1.1 Political geography: Territory of the megacity of Paris and the SIAAP

1.1.1.1 The megacity of Paris

The Île-de-France region is divided into eight *départements* (see Figure 1):

- Paris both a city and a *département*;
- Hauts-de-Seine;
- Seine-Saint-Denis;
- Val-de-Marne.

which form the *Petite-Couronne* (Paris and its surrounding *départements*). Beyond this is the *Grande-Couronne* (outer suburbs) with:

- Seine-et-Marne;
- Yvelines;
- Essonne;
- Val-d'Oise.

This territory, divided into 1,280 municipalities (*communes*), covers a surface area of 12,000km^2 and has 12 million inhabitants (Tabuchi et. al. 2016).

The megacity of Paris has no formal administrative existence making it hard to describe. The Ile-de France region consists of a group of municipalities forming a continuous built area[1] referred to as the Paris urban unit (*unité urbaine de Paris*). This definition has been adopted herein for the **megacity of Paris**; it consists of 412 municipalities with a population of 10.7 (2015) million inhabitants and a surface area of 2,845 km^2 (see Figure 2). The new administrative structure of the Greater Paris Metropolis (*Métropole du Grand Paris - MGP*) (Act of 25 January 2014) only covers part of the megacity, which equates to a quarter of its surface area and half of its population. It corresponds approximately to the *Petite-Couronne* or inner suburbs.

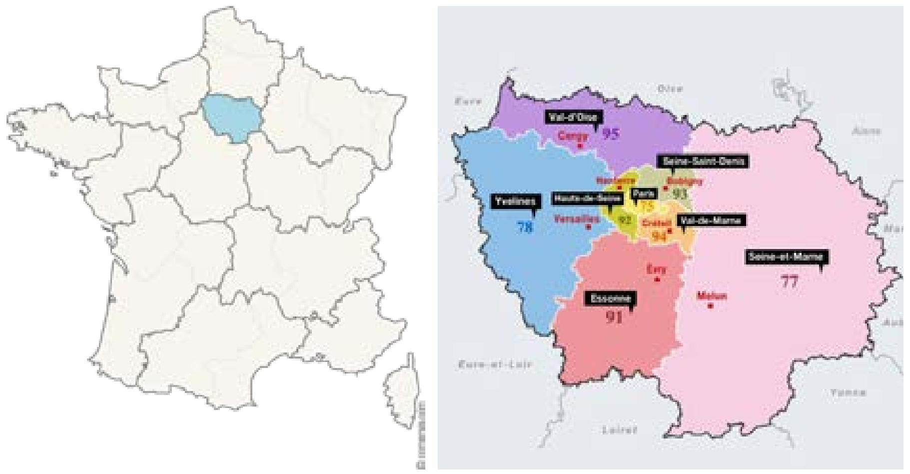


Figure 1. The Île-de-France region in France (left) and its eight départements (right)

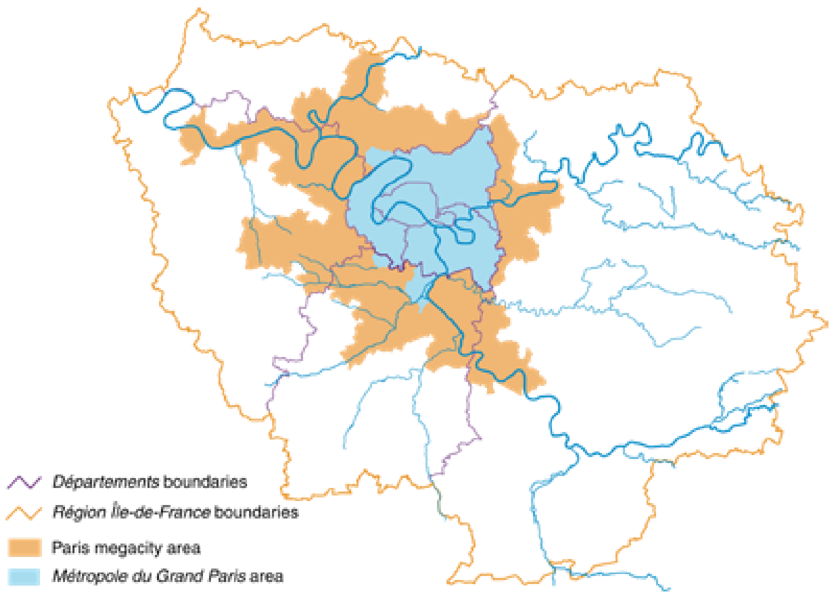


Figure 2. The boundaries of the Greater Paris metropolis and the megacity of Paris
(SIAAP - Source: INSEE, MGP)

Therefore, no consolidated data, including water management data, exist at the scale of the territory covered by the megacity of Paris. In addition, the data presented in this report relate to entities which are relevant to a particular activity: waste water treatment and drinking water, or to an administrative division: Ile de France region, *départements* and groups of municipalities.

1. The French National Institute of Statistics and Economic Studies (INSEE) defines an *urban unit* as a continuous, uninterrupted built area of more than 200 meters between two constructions.

1.1.1.2 The SIAAP institution

The SIAAP is responsible for sewage treatment for a territory that covers only a part of megacity of Paris. It is administered by the Petite-Couronne's *départements*, however its collection area also overlaps with the outer suburbs. This territory, with a total surface area of 1,800 km^2 consists of a total of 284 municipalities, which are home to 9 million inhabitants.

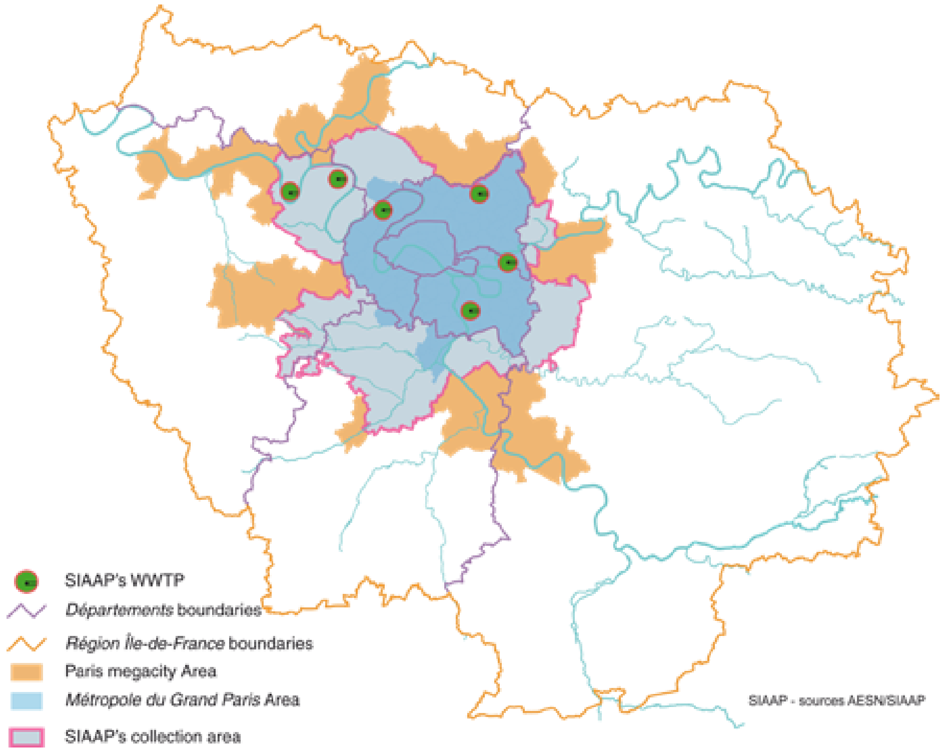


Figure 3. Map of the boundaries of the Greater Paris metropolis and the megacity of Paris
(SIAAP - Source: INSEE, MGP)

1.1.2 Climate and hydrology

1.1.2.1 Climate

The climate of the Paris region is temperate with an oceanic influence. The rainfall distribution is relatively consistent throughout the year and the temperatures are mild, in both summer and winter (see Table 1 and Figure 4).

Table 1. Annual precipitation levels at Paris-Montsouris

Year type	Precipitation level
Normally wet year (value exceeded one year in five)	738.9 mm
Average year	641.6 mm
Normally dry year (value not exceeded one year in five)	530.7 mm

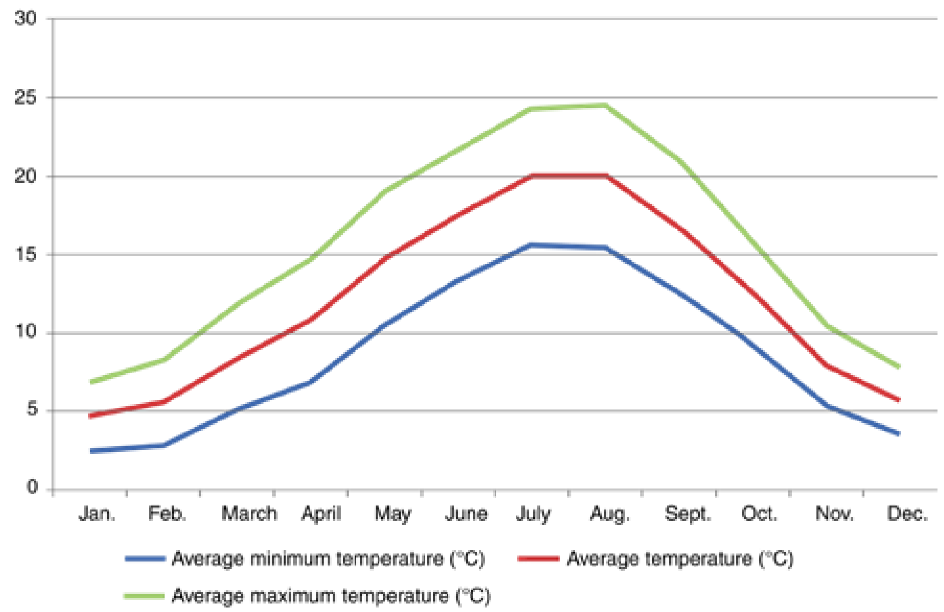


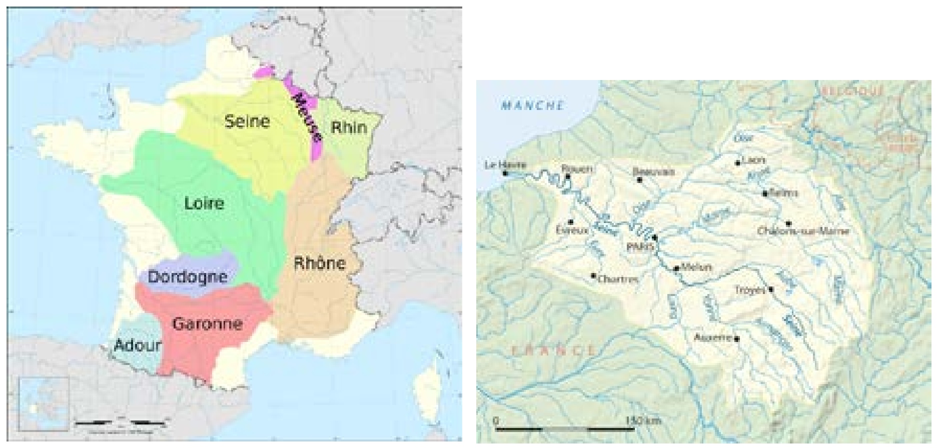
Figure 4. Average temperatures – 1970 – 2000

1.1.3 Hydrology

1.1.3.1 The hydrographical network

The megacity of Paris is situated in the Seine basin - one of the eight major French drainage basins (see Figure 5). It covers an area of 77,000 km^2. The major drainage axis is the Seine and its two main tributaries: the Marne and the Oise.

The main waterways, the rivers Seine, Oise, and Marne, are canalised and navigable. They play a major role in the supply of goods and also for the disposal of excavated soils and wastes from construction sites in Paris. These three waterways comprise the main water resources for the megacity of Paris.



A **B**

Figure 5. The major drainage basins in France (A) and the Seine basin (B)

1.1.3.2 Flow rate of the Seine

The median flow rate of the Seine in Paris, and the five-year and ten-year wet and dry flow rates, are low compared to other French rivers (Figure 6). The Seine and Marne have an oceanic regime[2] characterised by a low-flow period during the summer until the start of autumn and a flood period in February (due to low evaporation and high rainfall). The flow rates in these two rivers are controlled, for both high flow and low flow, by storage dams situated upstream of the basin area, thus limiting the impacts of natural flooding hazards.

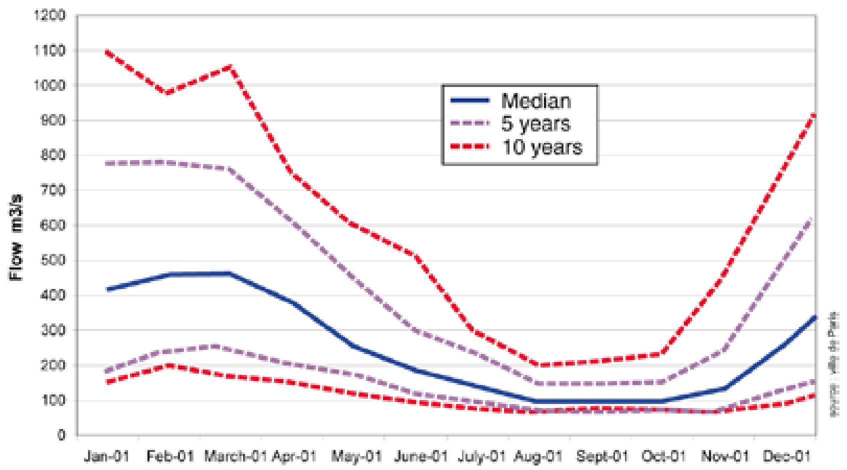


Figure 6. Five-year and ten-year flow rates of the Seine in Paris (source: Ville de Paris/AESN)

The main characteristic values of the Seine flow rate in Paris, and the Marne where it enters the megacity of Paris, are compiled in Table 2.

Table 2. Characteristic flow rates of the Seine in Paris and the Marne upstream of Paris

	Average	Low water (5-year) Average monthly flow rate	Low water (5-year) Daily flow rate over 10 days	High water (5-year) Average daily flow rate	High water (10-year) Average daily flow rate
Seine in Paris Austerlitz bridge	310 m³/s	82 m³/s	71 m³/s	1400 m³/s	1600 m³/s
Marne in Noisiel	109 m³/s	32 m³/s	27 m³/s	440 m³/s	500 m³/s

1.1.3.3 Flow control on the Marne and the Seine

As for any hydrological system, the Seine and the Marne are subject to high and low flow periods, but the extent of the development of the Paris conurbation has made it particularly vulnerable to these natural phenomena, and to flooding in particular. The floods of 1910 and 1924, but also the drought of 1921, prompted the French government and the local political authorities to adapt the Seine catchment in response to these hazards. The final works were completed in 1990.

The *Seine Grands Lacs*[3] public institution currently manages 850 Mm³ of storage capacity designed to mitigate flooding, provide alleviation of low flow and help to meet the water use needs of the megacity of Paris as well as the cooling needs of the nuclear power station at Nogent-sur-Seine. As an illustration of the alleviation of low flow provided by the reservoirs, 40% of the minimum annual flow of approximately 85 m³/s for the Seine in Paris comes from storage dams.

2. Oceanic regimes are a characteristic of western European climate: under the influence of Gulf Stream in Atlantic Ocean, the climate is cool with high rainfall in winter. Low evaporation added to rainfall means more runoff and a higher flood hazard.
3. The *Seine Grands Lacs* regional public corporation is administered by the *départements* of Hauts-de-Seine, Seine-Saint-Denis, Val-de-Marne and Paris, which own the large lakes upstream of the Paris region

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1.1.3.4 A megacity on a small river

The Seine, which drains the pollution generated by 14 million inhabitants in the Paris region has a very low discharge dilution capacity, especially during its seasonal low flow period in summer and autumn (Figure 6) which is significantly below that of other river basins in France (Table 3).

Table 3. Comparison of minimum water flows and dilution capacity of different French rivers

	Five-year minimum water flow	Conurbation	Population	Impacts
	m³/s		Millions of inhabitants	Dilution capacity
Rhine	520	Strasbourg	0.7	65 m³/d/inhabitant
Rhône	380	Lyon	1.8	18 m³/d/inhabitant
Seine (at Poissy)	170	Paris urban unit	10.5	1.4 m³/d/inhabitant

Box 2. Greater Paris Region demography and territory

Demographic data

The urban growth of the megacity naturally began in the city of Paris (until 1930). It continued in the inner suburbs and then into the outer suburbs (*Grande Couronne*) from the 1960s onwards.

Due to its density, the city of Paris corresponds to a 'dense city' model, whose consequences include very high use rates of all networked infrastructure systems, including drinking water, sanitation, and public transport, with a peak during the daytime as the resident population of 2.2 million inhabitants of the City of Paris expands to nearly 3 million including commuters (see Table 4).

TABLE 4. Demographic data on the Île-de-France region (2012) and average sizes of households

Département	Surface area (km²)	Population (2012)	Density (inhabitants/km²)	Average size of households
Paris	105	2,240,621	21,300	1.9
Hauts-de-Seine	176	1,586,434	9,010	2.3
Seine-Saint-Denis	236	1,538,726	6,520	2.6
Val-de-Marne	245	1,341,831	5,480	2.4
Paris & inner suburbs	657	6,707,612	6,800	
Essonne	1,804	1,237,507	690	2.6
Val-d'Oise	1,246	1,187,081	950	2.7
Yvelines	2,285	1,412,356	620	2.6
Seine-et-Marne	5,915	1,353,946	230	2.6
Outer suburbs	11,250	5,190,890	460	
Megacity of Paris	2,845	10,550,350	3,710	
Île-de-France	12,012	11,898,502	990	2.4

Source: (https://www.insee.fr/fr/statistiques)

Occupation of space

- 20% of the Île-de-France region is occupied by urbanised areas (roads and buildings);
- 13% by built areas (housing and buildings);
- 53% crops;
- 23% woodland (23%).

On the other hand, for Paris and the inner suburbs, urban space occupies 84% of the territory and built areas occupy 60%. Rural space is very limited (16%).

Economic data

The Île-de-France region is ranked highly in the global economy. In 2012, its GDP of €612 billion made it the sixth-ranked metropolitan area after Tokyo, Greater New York, Los Angeles, Osaka and London.
With over 5.9 million jobs, 85.5% of which are in the tertiary sector, Île-de-France stands out due to its dominant position in the national economy and the size of the tertiary sector, although it remains highly diversified in relation to other cities of a similar size. Despite a high level of de-industrialisation, it remains France's leading industrial region. Its agriculture—mainly devoted to cereal crops—is amongst the most productive in France and tourism is a major industry (33 million hotel nights in 2013).

1.2 SIAAP and the sanitation at the heart of the megacity of Paris

The SIAAP, created in 1970, is the public utility in charge of the transport and treatment of wastewater for the Greater Paris region. SIAAP is the operator located downstream of a large sewage collection and transport system for a drainage area of 1800 km^2 and serving 9 million inhabitants. The SIAAP plays a key role as it treats the sewage produced by 9 million inhabitants. As operator of the main sanitation system on the Seine catchment, it is also responsible for the impact of the sanitation system on the natural environment. Furthermore, the SIAAP is, as are many other sanitation utilities around the world, playing an increasing role in a carbon-free and a circular economy.

The sanitation scheme for the conurbation has evolved over time. In 1929, the principle was to concentrate all of the wastewater at a single plant downstream of the conurbation. In 1968, this single-plant concept was abandoned, at a time that coincided with the emergence of the first institutional decentralisation measure for the conurbation (see Figure 7).

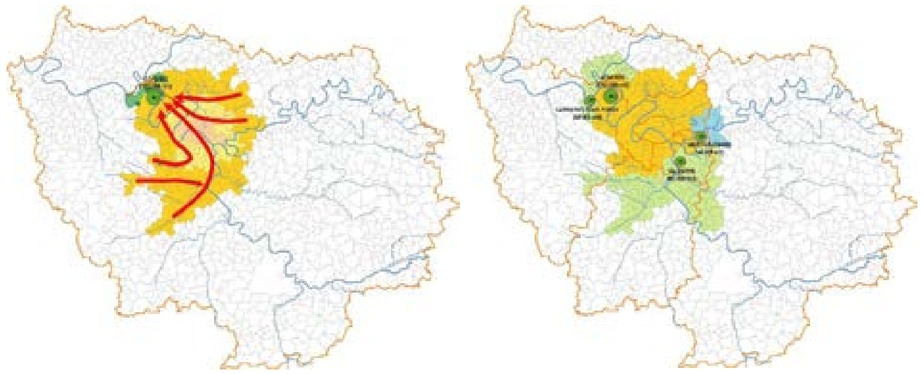

Figure 7. Greater Paris region sanitation program in 1929 (left) and 1968 (right)
(Source: SIAAP)

A modern master plan was adopted in 1997. It established the broad directions of the sanitation policy currently in force in the central area of the megacity. The plan was the subject of an agreement between the SIAAP, the Île-de-France region and the Water Agency. The main goal was to limit the volume treated at the *Achères – Seine-Aval* downstream wastewater treatment plant. The reason for this downsizing of treatment capacity was because of local complaints related to odor nuisances caused by the WWTP. A new sharing of the treatment capacity between six WWTP was then decided. The creation of stormwater storage/release basins was also recommended in order to reduce pollution during rainy weather.

Since then, the master plan was revised in 2007 with a consultation extended to the SIAAP's constituent *départements* and to the inter-municipal regulatory authorities linked to the SIAAP. A new revision has been approved in 2017. It places particular emphasis on controlling pollution in wet weather, which is the main cause of failing to achieve the targets of the European Water Framework Directive (WFD). It takes account for the population increasing from 8.8 million inhabitants in 2009 to 9.6 million in 2030, water consumption declining from 59 m^3/inhabitant/year to 52 m^3/inhabitant/year and, above all, the run-off surface area connected to the sanitation system (see 1.2.2.2) stabilising at the current value of 252 km^2.

1.2.1 A multi-operator system

Within the region covered by the SIAAP, the collection, conveyance and treatment of wastewater are divided among several operators (Figure 8):

1. Collection: the municipalities or consortia thereof, are responsible for the basic collection of urban wastewater as well as stormwater throughout a 15,000 km system. This is an essential level because it determines the quality of the wastewater collection and the control of stormwater;
2. Conveyance: the *départements* of Paris, Hauts-de-Seine, Seine-Saint-Denis, Val-de-Marne and, in the outer suburbs, the inter-municipal sanitation authorities (*syndicats intercommunaux d'assainissement*), are responsible for the intermediate conveyance between the authorities responsible for the basic collection and the transfer sewers leading to the wastewater treatment plants;
3. Treatment: the SIAAP is responsible for the final conveyance to its wastewater treatment sites. Some of SIAAP's main sewers are operated by the four *départements* mentioned above.

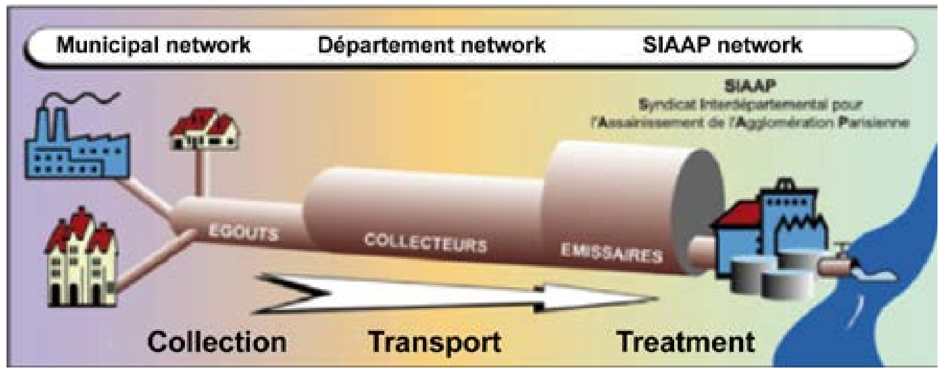

Figure 8. Flowchart showing the waste water collection and treatment in the megacity of Paris.
Source: https://www.seine-saint-denis.fr/IMG/jpg/reseaudea72-2.jpg

1.2.2 Sanitation infrastructure

1.2.2.1 Wastewater treatment plants

The SIAAP has completed the construction of the 6 wastewater treatment plants planned in 1997 (see Figure 9). In 2006 the SIAAP had reached sufficient treatment capacity to handle all the sewage produced (see Table 5). Nevertheless, the modernisation of the oldest plant *Seine-Aval* is still underway. These works should constitute the last stage in ensuring the good physico-chemical status of the Seine, a requirement of France's European commitments for 2021.

Seine-Aval plays a key role in the system. This due to its historical position in the system: this WWTP was the focus point of the sewer system. For this reason, most of the sewage flows to it. The second point is related to its capacity, as it is SIAAP's largest WWTP. This means that *Seine-Aval* plays the role of an 'expansion tank'.

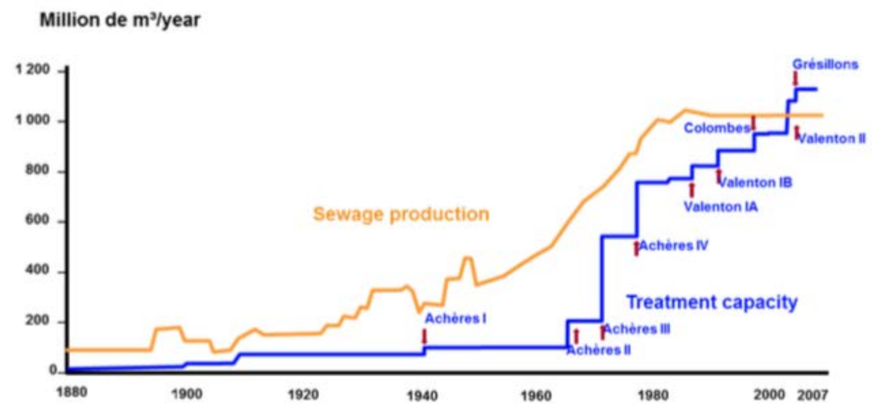

Figure 9. Long-term evolution of sewage production and WWTP capacity in Greater Paris

Table 5. Capacities of the SIAAP plants in person equivalents

Treatment Plant	Person Equivalent (PE) capacity	
	Optimum capacity	**Biological treatment capacity in rainy weather**
Seine-Aval at Saint-Germain-en-Laye (Yvelines)	4,182,000 PE	8,218,000 PE
Seine-Amont at Valenton (Val-de-Marne)	2,618,000 PE	4,000,000 PE
Seine-Centre at Colombes (Hauts-de-Seine)	982,000 PE	982,000 PE
Seine-Grésillons at Triel-sur-Seine (Yvelines)	1,149,000 PE	1,322,000 PE
Marne-Aval at Noisy-le-Grand (Seine-Saint-Denis)	500,000 PE	605,000 PE
Seine-Morée at Blanc Mesnil (Seine-Saint-Denis)	300,000 PE	351,000 PE
Total	9,731,000 PE	15,478,000 PE

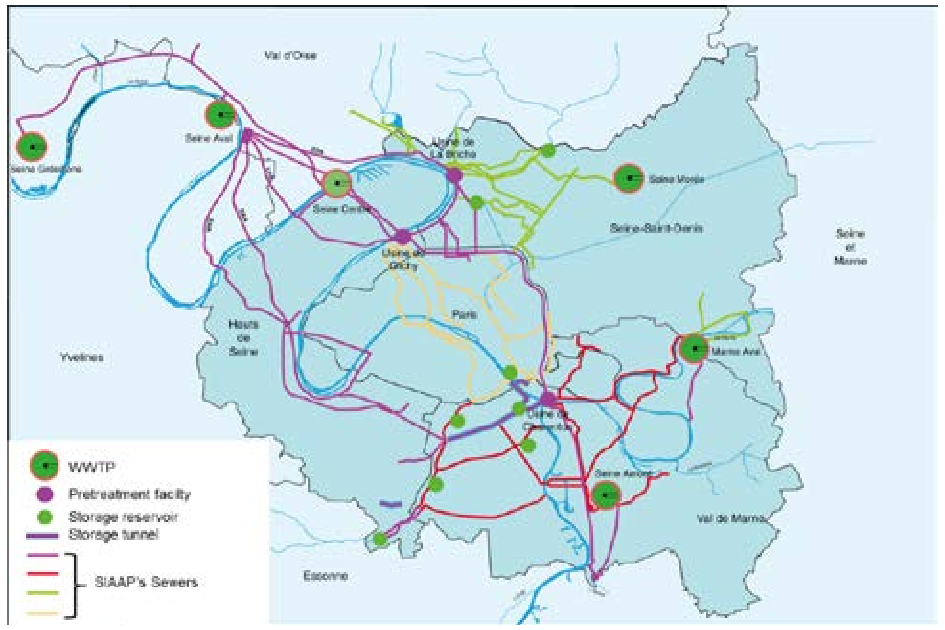

Figure 10. Location of the SIAAP's major facilities (violet: Sewers operated by SIAAP, Sewers orange: operated by Paris, green: Sewers operated by Seine-Saint-Denis and red: Sewers operated by Val-de-Marne)

1.2.2.2 Sewage collection and transport systems at the heart of the megacity of Paris

A vast collection and conveyance system, with an estimated length of 15,000 km, has been created over time in line with the growing urbanisation of this region.

In many cases, the Paris region sanitation is based on a combined sewer system in its center part and on a separate system in its outskirts, which was developed more widely after the Second World War (see Figure 11).

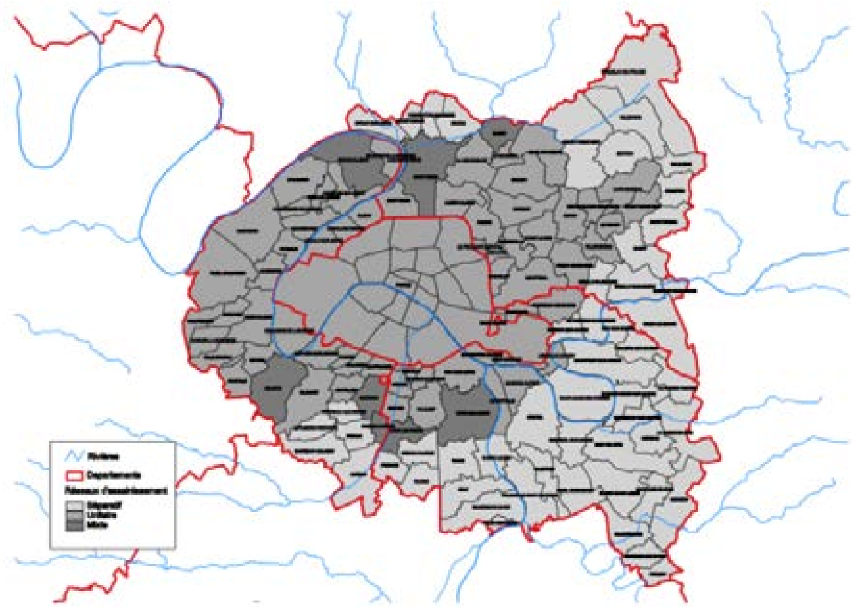

Figure 11. Typology of sewage collection inside SIAAP's administrative boundaries: Light grey: separate system, medium grey: combined system and dark grey for mixed system

Table 6. Breakdown of the linear length of the main sewers owned by the départements

	Paris	Hauts de Seine	Seine-Saint-Denis	Val-de-Marne
Combined sewers	2,100 km	384 km	356 km	195 km
Stormwater		74 km	190 km	377 km
Wastewater sewers		72 km	124 km	261 km
Total	2,100 km	530 km	670 km	833 km

In addition to the treatment plants belonging to the SIAAP and the main networks stated above, the Greater Paris region sanitation system consists of:

- stormwater storage facilities with a total capacity of 2.5 million cubic meters;
- 200 combined sewer overflows (CSOs), with 10 of them which are representing over half of the discharged volume;
- numerous electromechanical pumping stations and stormwater outlets;
- highly sophisticated real-time wastewater and stormwater management systems (see sections 1.2.2.5 and 3 below).

1.2.2.3 Sewage composition

Sewage treated by the SIAAP is composed of various sources of water, with wastewater contributing around 60% of the total annual volume arriving in SIAAP's treatment plants (see Figure 12). Infiltration water contributes approximately 25%, stormwater approximately 5% and specific to Paris region: the non-potable water used in Paris city for street cleaning and for sewer flushing to remove solid deposits and 10% of stormwater mainly related to combined sewers.

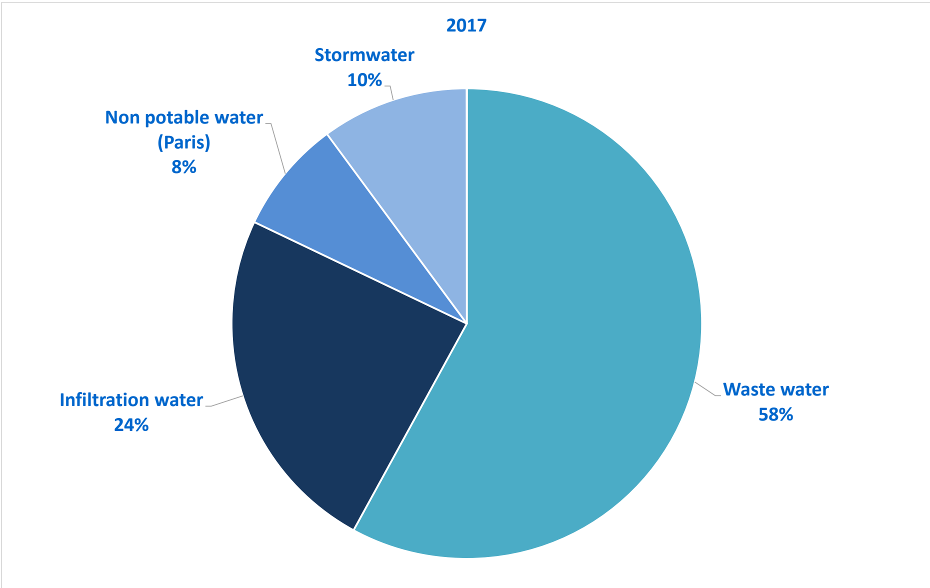

Figure 12. SIAAP's sewage composition – 2017

The percentage of the different kinds of water depends on the annual amount of rain (see Figure 13).

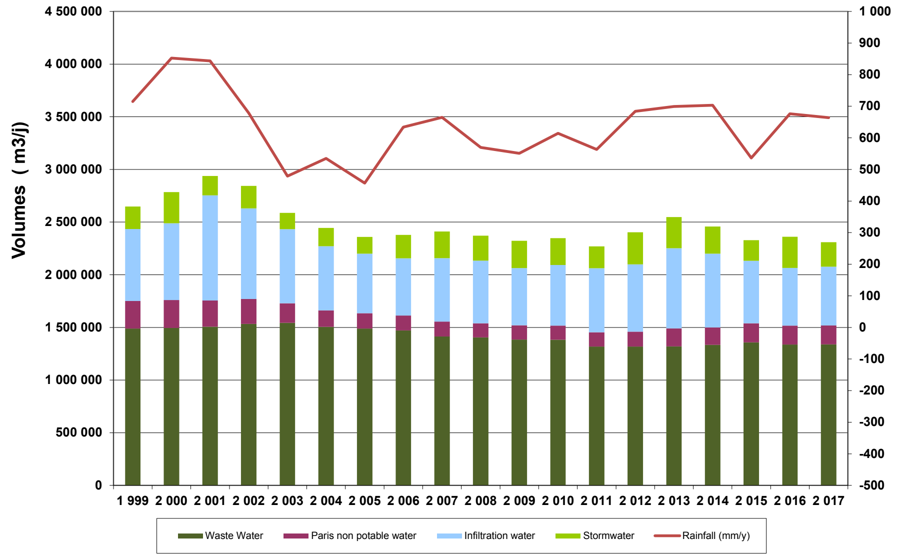

Figure 13. Annual variation in different kinds of waters entering in sewage composition

1.2.2.4 Stormwater storage facilities

SIAAP has a stormwater storage capacity of 955,000 m^3, of which 270,000 are in the form of reservoir tunnels. SIAAP and its départements have a total storage capacity of 2.5 Mm^3. These assets consists of underground or open air storage tanks but also reservoirs tunnels.
These storage facilities are multipurpose works with aims to handle sewer overflow caused by cloudburst and to reduce stormwater pollution during small to average rain events. Some facilities are located on a separate stormwater network but most of them are connected to combined sewers. The polluted part of the stored water is diverted to one of SIAAP's treatment plants.

1.2.2.5 Real-time Control system (RTC) (see section 3)

Historically, stormwater management systems have been implemented primarily by the départements to manage flows in rainy weather, particularly in order to counteract the risks of flooding due to the overflowing of systems. This drove them to started investing in real- time management at a very early stage, in the late 1970s. Seine-Saint-Denis, the pioneer, started to implement its first local RTC station in 1974 for the management on a stormwater storage facility. Ten years after they had a complete remote control system: NIAGARA (*Nouvelle Interface Applicative de Gestion Automatisée du Réseau d'Assainissement*). Seine- Saint-Denis was followed by Hauts-de-Seine with GAIA (*Gestion Assistée par l'Informatique de l'Assainissement*), Val-de-Marne with VALERIE (*Val-de-Marne régulation informatisée des effluents*), Paris with GAAPSAR (Gestion Automatisée de l'Assainissement Parisien) and SIAAP with SCORE (*Système de contrôle et de régulation des émissaires*). Today, each operator possesses a system adapted to its specific constraints, with the dual aim of combating flooding and protecting the receiving water. These real-time control systems are now interconnected and the different operators communicate with each other.

One of the unique characteristics of SIAAP's system is the existing interconnection capacities among the wastewater treatment plants. This ability to transfer flows among treatment plants is a rare enough occurrence worldwide to be worthy of mention here. The management of this system is made with MAGES or SIAAP sewage Management Assistance Model. The full description of this Smart Water Management (SWM) system is developed in the following section 3.

2. Water Challenges

2.1 Recovery of water quality in the Seine

The Seine is not a large river when compared to the population settled in its catchment: around 14 million inhabitants rely on a flow as low as 95 m^3/s on average of every 5 years. During the last five decades, the challenge was the recovery of water quality within the Seine through and downstream of Paris, and to reach the good status stated in the European WFD (2000/60/EC of 23th October 2000). This means that one of the key water challenges is maintaining the quality of the receiving water.

The WFD and its incorporation into French law (especially the Order of 25th July 2015) currently set the targets to be achieved in addition to the procedures and criteria for assessing water quality (see Table 8).

Urban development led to deterioration in the quality of the Seine's water, from early observations in the 1870s until the 1970s. During the last 35 years, the physico-chemical quality of the water in the Marne and Seine has improved very significantly both upstream and downstream of the conurbation (Figure 14, figure 15 and Figure 16). The figures represent ammonia evolution through fifteen years with a first step of improvement in 2007 and a second step in 2012 due to works on *Seine-Aval* Waste Water Treatment Plant. They compare the changes between 1971-1972, 1985-1986 and 2012-2013 with regard to four parameters (dissolved O_2, BOD_5, NH_4+ and PO_4^{3-}).

These improvements are largely due to the general policy of developing sewage treatment plants. However, downstream of the megacity of Paris, the nitrogen and phosphorous concentrations still do not meet the WFD good status targets. Works are being carried out on the *Seine-Aval* wastewater treatment plant situated downstream of Paris megacity (see 1.2.2.1), so that it can make a decisive contribution to achieving good water status in the Seine pursuant to the targets set by the Water Framework Directive.

Table 8. French physico-chemical criteria for the receiving water quality

QUALITY PARAMETERS	QUALITY LIMITS				
	VERY GOOD	GOOD	MEDIUM	POOR	BAD
OXYGEN BALANCE					
Dissolved oxygen (mgO_2/l)		8	6	4	3
Dissolved oxygen saturation rate (%)		90	70	50	30
BOD_5 (mgO_2/l)		3	6	10	25
Dissolved Organic Carbon (mgC/l)		5	7	10	15
TEMPERATURE					
Salmon stream		20	21,5	25	28
Cyprinid stream		24	25,5	27	28
NUTRIENTS					
PO_4^{3-} (mg $PO_4^{3-}.l^{-1}$)		0,1	0,5	1	2
Total Phosphorus mg P/l		0,05	0,2	0,5	1
NH_4^+ (mg $NH_4^+.l^{-1}$)		0,1	0,5	2	5
NO_2^- (mg $NO_2^-.l^{-1}$)		0,1	0,3	0,5	1
NO_3^- (mg $NO_3^-.l^{-1}$)		10	50	*	*
ACIDIFICATION					
pH minimum		6,5	6,0	5,5	4,5
pH maximum		8,2	9	*	*

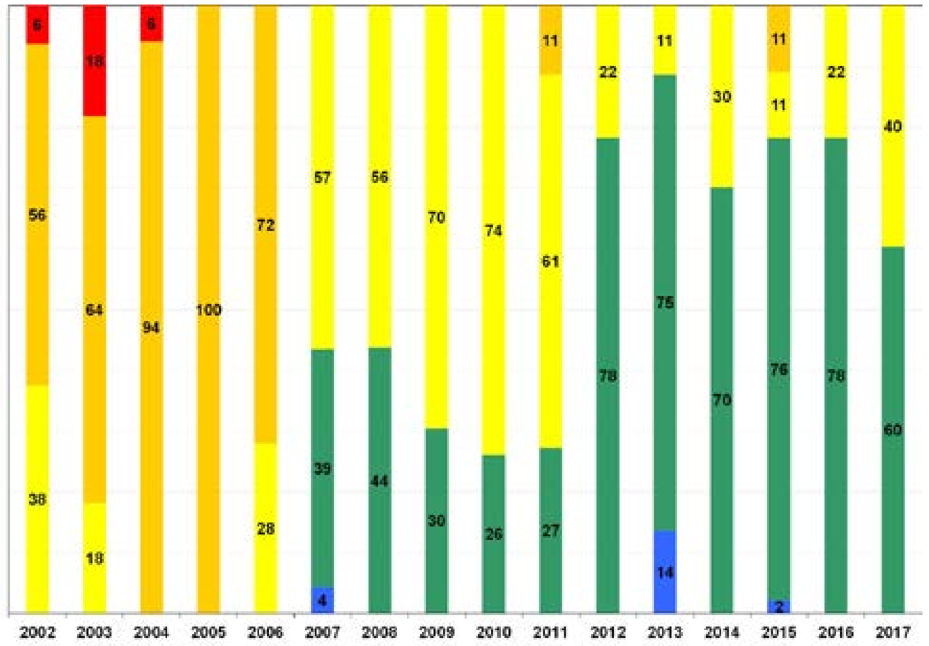

Figure 14. Evolution of the Seine dowstream of Paris (Poissy monitoring station) region for ammonia – Percentage of time in compliance with French environmental standards (SIAAP)

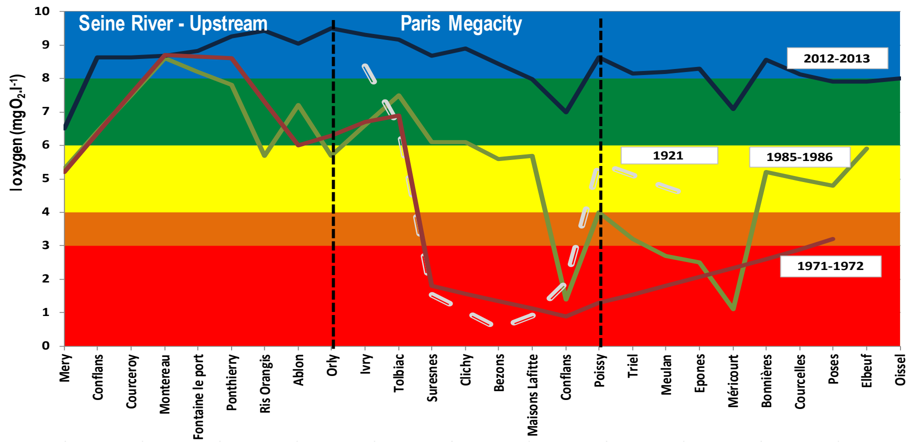

Figure 15. Changes in dissolved oxygen concentrations in the Seine in 1971-1972, 1985-1986 and 2012-2013 (Rocher and Azimi 2017)

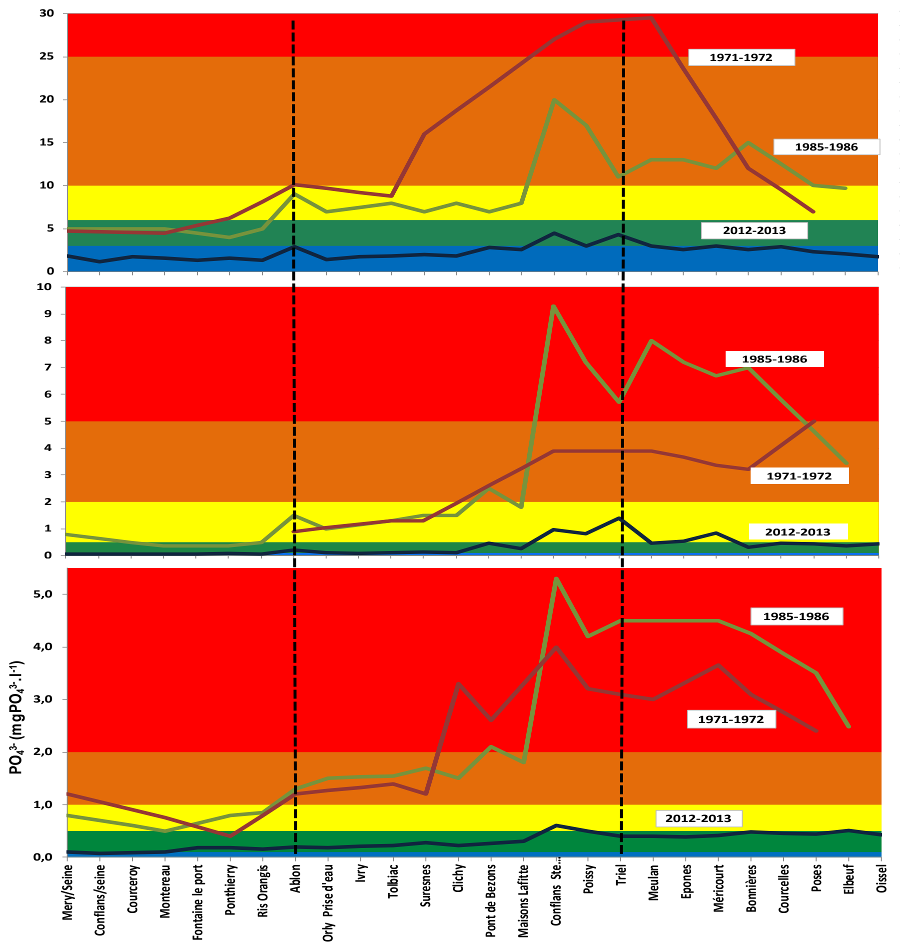

Figure 16. Changes in concentrations of carbonaceous (BOD5), nitrogenous (ammonium) and phosphatic (ortho-phosphates) pollution in the Seine in 1971-1972, 1985-1986 and 2012-2013 (Rocher and Azimi 2017)

With regard to micro-pollutants, the 2013 status review as part of the WFD reveals a less satisfactory situation, especially due to the presence of polycyclic aromatic hydrocarbons (PAH).

The monitoring of fish stocks carried out since 1990 by the SIAAP, however, provides an overview of the significant improvement in stocks in the Seine over the last 25 years. In this time, the number of species counted during electro-fishing operations rose from 12-14 to more than 20, with an accumulated total of 32 species counted during the operations[4] (see Figure 17). We can now observe the presence of species considered to be sensitive to pollution like salmon.

4. Bleak, eel, common barbell, Amur bitterling, white bream, common bream, pike, crucian carp, common carp, sculpin, chub, sticklebacks, common roach, gudgeon, ruffe, nase, ide, perch, pumpkinseed, catfish, common rudd, zander, wels catfish, tench, and dace.

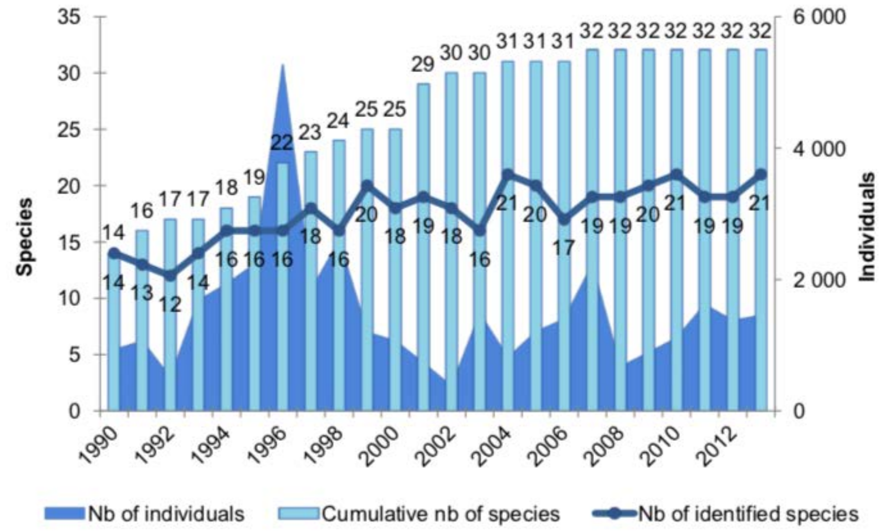

Figure 17. The number of species and individual specimens counted in the Seine per fishing year and the accumulated total over the period of study (1990-2013) (Azimi and Rocher 2016)

2.2 Growing population in the Paris megacity

Throughout the SIAAP's administrative territory, a 9%[5] increase in the population is anticipated over the 2012 – 2030 period, which amounts to practically 1 million inhabitants whose arrival may have a significant impact on water management: water supply, wastewater collection and management of the impervious surfaces of new development areas.

2.3 The effects of climate change

The effects of climate change on the hydrology of the Seine have been examined primarily in the framework of several research projects[6], in partnership with operational stakeholders. All of these projects will result in major changes to the hydrology of the Seine basin area from 2050 onwards: water resources may no longer be abundant. At the same time, there are no clear statistical signals concerning a change in the flood hazard.

The main conclusions are as follows:

- An increase in air temperatures of 2.3°C for the annual average temperature and as much as 3°C in summer;
- A downward trend for summer rainfall with strong uncertainties about the rainfall characteristics but of lesser importance than the increase in the evaporation rate;
- The rising air temperature will significantly increase the potential evapotranspiration demand. At the scale of the Seine catchment, this will strongly reduce aquifer recharge and lower the flow rates of rivers;
- The low flow rates of the Seine, with very similar rules for low flow support by storage dams to those in force today, will drop significantly from 2050 onwards. A drop of between -10 and -50% in the mean annual flow rate of the Seine in Paris is anticipated, depending on the models used. The drop in the five-year low flow rate could be as much

5. Hypothesis adopted by the SIAAP for the 2015 revision of its sanitation plan in agreement with government authorities.
6. 'RexHySS', carried out by a multidisciplinary team from 2007 to 2009, allows for the estimation of the consequences of climate change on the hydrological regime of the Seine by 2050 and 2100
'Climaware', for which some of the research concerned the Seine basin and the role of storage dams seeks to propose adaptation strategies for water management in response to the impacts of climate change on surface waters.
'Explore 2070' program simulates a horizon of 2045 – 2065 based on the A1B climate change scenario of the Intergovernmental Panel on Climate Change (IPCC).

as 60%. This decrease is simulated on the basis of the current abstractions and land uses. The changes concerning ten-year return period floods are less consistent and are generally statistically less significant;
- In aquifers, the groundwater table will lower by 1 to 5 meters compared to today's level, impacting the main supply sources for rivers.

The results obtained show that by 2050, the highest probabilities concern the drought hazard. Therefore, more studies and research need to be carried out in this field, specifically concerning the impacts of changing agricultural practices on water requirements, changes in the management of these structures and in their characteristics, and the changes in drinking water consumption for domestic uses. The main issue relating to climate change concerns the risks of a deterioration in water quality as a result of the drop in the low flow rates of rivers. Overall, the pollution loads discharged by the urban wastewater treatment plants situated in the upstream basin areas of the Seine are likely to remain stable, as the population will not increase as much as in the Paris region[7]. Any drop in the rate of flow should thus lead to higher concentrations in the water. The megacity of Paris will thus face a twofold problem, with a reduction of the dilution capacity for these discharges due simply to the drop in flow rates, which will be magnified by the highly likely increase in concentrations in the Seine, Marne and Oise. At the same time, the rise in the population of the megacity will increase the pressure on treatment systems. In this context, if one assumes that sustainable development is based on keeping water quality in a good condition for the next generation, maintaining the water quality within the Seine becomes a very important issue.

An analysis undertaken by government agencies and all stakeholders has allowed for the performance of a shared diagnosis concerning the sustainability of the Paris conurbation, especially—but not exclusively—in the water sector. The findings can be summarised in the following manner:
- With regard to drinking water, the report concludes that 'Modifications to the hydrogeological regime in response to climate change could significantly modify the current fragile balance, with a reduction in the flow rates of the major rivers in summer, a seasonal increase in agricultural needs in particular, a rise in temperatures and in evapotranspiration, new requirements relating to adaptation to climate change, etc. Groundwater resources, which supply many local authorities in the outer suburbs, are dependent on how surface soils are used, and are damaged by the increased concentrations of pesticides and nitrates associated with agricultural practices. Changing these practices has emerged as a general challenge: a model that uses inputs and water more sparingly must be sought;
- Regarding sanitation: the report stresses that 'the consequences of climate change for the dilution capacity of wastewater will be an essential factor in maintaining the good status of surface water bodies. At the Ile-de-France level, the discharges and abstractions will certainly increase the pressure exerted by the Paris conurbation on aquatic environments and the already vulnerable water resources, in a context of heightened tensions due to climate change'.

2.4 Flood protection

The first type of floods caused by rivers like the Seine or Marne are not in the SIAAP mandate, however, the operation of the sanitation system can be severely affected by Seine or Marne flooding. In those conditions, the SIAAP has to ensure good conditions for the sanitation of Paris Region: the SIAAP then operates the system in close cooperation with all its other partners in order to provide stormwater drainage and to avoid sewer overflow floods or any shutdown of the sanitation system.

7. Waste Water Treatment Plans (WWTPs) are based on traditional activated sludge with high-level performance, in particular in relation to the major parameters such as Biochemical Oxygen Demand (BOD) and ammonia. Concerning nitrate, the current regulation obliges domestic WWTP to remove 70% of the total nitrogen. Today the main nitrate contributor is agriculture.

The second type of flooding, which is of concern, are those caused by heavy rainstorms that overload the sewer system. These floods are more strongly related to SIAAP's sanitation tasks and even though the SIAAP is not formally in charge of the management of stormwater, it has to pay attention to this issue particularly in some parts of the Paris region. This was the starting point of Real-Time Control development in Paris region (see section 3.2.2).

Box 3. How the Seine quality recovery challenge been addressed in the past

The result in the Seine quality improvement is the consequence of a long-term policy started in the mid-1960s. To address the poor water quality of the French rivers, a Water Act was voted in 1964. This first Water Act was original in several points, with the key points as follows:
- Integrated water management based on the main French rivers basins and not on the administrative limits;
- A new governance with a basin committee where the water management policy is defined by the water users: cities, industries, farmers, environmental associations, fishing professionals and State authorities;
- Water agencies per basin were created. These agencies are in charge of the financial part of the water management policy by collecting fees based on the pollutant emissions and by encouraging works and actions by providing subsidies.

This is the base of the water management policy in France. Thanks to this policy and these tools, the SIAAP has launched a continuous program of works in order to improve its WWTP capacity and performance. This program became more ambitious during the last two decades.

Figure 18 below shows the history of sanitation in Paris region. Its only since the end of 1990's the treatment capacity is sufficient enough to treat all the collected sewage.

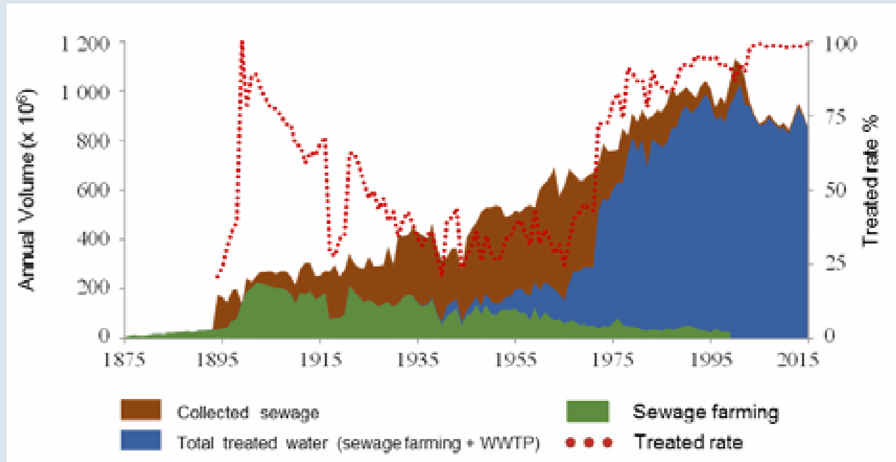

FIGURE 18. Volume evolution for collected and treated wastewater by sewage farming and centralized treatment in conventional treatment plants from 1875 to today
(Rocher and Azimi 2017)

3. Smart Water Management Solution

3.1 MAGES presentation, how does it address the Paris region water challenge?

The development and implementation of the smart water management systems in Paris region is the result of a long process originally related to local floods during cloudburst events. Since that time, the sanitation system has gone through major changes in its structure and in its regulatory frame (Blanchet et. al. 2008; Tabuchi and Blanchet 2016).

As stated above, today sanitation of Paris region relies on a multi-stakeholders management organization, a vast sewer system to collect and transport the 2.4 Mm^3/d produced by 9 million inhabitants, on 6 interconnected WWTP and all the system is of a high impact risk for the receiving waters. After the time of development and implementation of local real time control system, then came the time for a comprehensive vision of sanitation system operation. This appeared to be increasingly necessary to efficiently manage this interactive and complex system on which rely the Seine quality recovery to comply with WFD objectives.

In 2001 the SIAAP decided to build a new real time control system on the base of the existing systems. This new RTC had to allow in real time, data and information exchanges between the different system, to provide a comprehensive overview of the status of the system and to produce operation scenario. This system, described herein after is based on hydraulic and hydrologic numeric models fed by continuous monitoring of the sewage network and weather forecast-based radar images. After a presentation of MAGES context and origins, the following paragraphs provide a comprehensive description of the developed solution and the main results obtained thanks to the implementation of this decision support system in SIAAP's sanitation system.

3.2 MAGES context and origins

3.2.1 The technical context

The network under SIAAP's control consists of large collectors and main sewers, built at depths varying from 3m to 100m, depending on the topography, and whose diameter varies between 2.5m and 6m. Its total length is about 400 km. Numerous system interconnections have been created to guide flows according to the available capacity of downstream main sewers, storage and treatment works and also to allow by-pass without spillage of untreated water to receiving water during maintenance operation. One of the very special characteristics of the Paris agglomeration is its high water transfer capacity between WWTPs. Although it is common in large cities to find several wastewater treatment plants, it is rare that they have the possibility of transferring water between them through an interconnected sewer network. This feature is the fruit of the history of the agglomeration. This is mainly due to the fact that originally the system was designed with a WWTP downstream of Paris region. In 1968, a sanitation master plan was adopted with the idea of splitting the collection zone and with a new distribution of treatment facilities around the agglomeration. This treatment facility's new distribution was strengthened the 1997's sanitation master plan which main conclusion was the decision to downsize *Seine-Aval* WWTP from initial capacity of 2.7 Mm^3/d to 1.3 Mm^3/d. This evolution from a single treatment site to a multi-site approach implanted on a main transport network has been a favorable factor and it has been taken advantage of to reinforce this link between the treatment plants. The flow management system takes great advantage of this feature.

Concerning *Seine-Aval* downsize, regarding to the original design of the sewers, the consequence is a decrease of water velocity which, added low slopes, drives to a high sensitivity of the sewage transport network to solid deposits. This is a problem when a strong rain event occurs after a long dry weather period: the consequence is a very high suspended solids concentration.

The other important aspect is the water management in rainy weather. In order to reduce the combined sewer overflow (CSO) frequency, volumes and their impact on the receiving environment, 955 000 m^3 of storage tanks and reservoir tunnels were built to ensure the storage of the polluted water and their released to the treatment plants.

Approximately 150 local management stations with remote-controlled regulating and pumping equipment have been deployed in the SIAAP's area of competence and allow the implementation of a real-time control of the works.

At last, among the important technological developments, the treatment processes implemented at SIAAP rely heavily on biofiltration, which is distinguished by the short residence time of the effluents, less than 2 hours. This means that the treatment systems are very responsive with very little buffer time. This is an advantage for example for adapting the wastewater treatment to the requirements of the receiving water protection, it's also sometimes a disadvantage: the operation of such a system can be difficult due to its reactivity.

3.2.2 The road taken from SCORE to MAGES

In the late 1980s, SIAAP developed a real-time control system, called SCORE to address the significant shortage of effluent treatment capabilities. At that time, only 3 WWTP were operational, the capacity deficit was around 500 000 m^3/d and they only concerned the 'Western system[8]' related to the *Seine-Aval* plant whose project was then to increase its capacity from 2.1Mm^3/d to 2.7 Mm^3/d. In an interim stage, the idea was to take advantage of the sewer pipes' ability, in dry weather, to store the daily peak of the effluents and to treat the sewage during the night, when the flow is lower. However, one had to be sure not to take risks in the face of floods during rain events. The two graphs below (Figure 19 and Figure 20) show the results of flow control in order to smooth the hydrograph between night and day. The first one illustrates the regulation obtained with SCORE at its beginning. At that time the average flow rate capacity of *Seine-Aval* WWTP was around 25m^3/s. The table also shows the improvement of flow control from year to year.

SCORE was based on the system of five main sewers supplying Seine-Aval which were equipped with regulating valves. Each main sewer was divided in several trunks used for sewage storage. Given the hydraulic risks associated with the rains, this system already included a rain forecast. The remote management system was the precursor of the current system and was began operation in 1992. It was independent from those implemented by each *département* (see section 1.2.2.5).

8. The 'Western system' is the downstream part of SIAAP's sanitation system. It is based *Seine-Aval*, *Seine-Centre* and *Seine-Grésillons* treatment plants which are interconnected and located in the West side of Paris region.

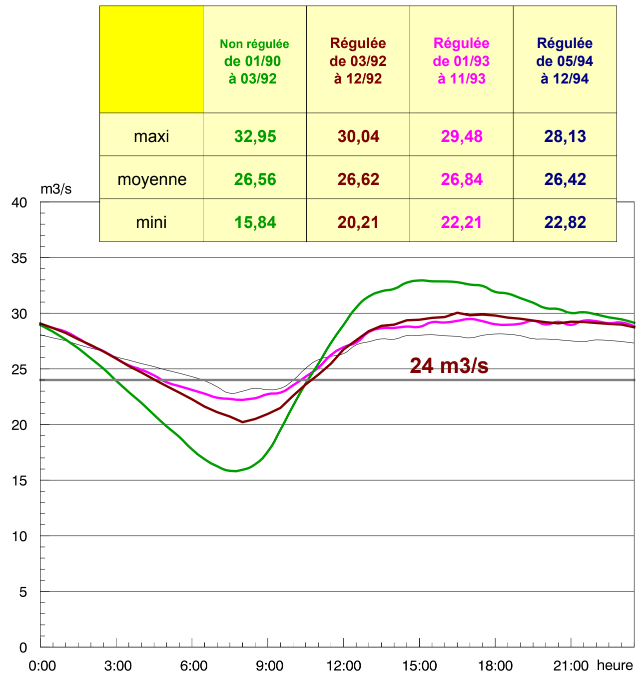

Figure 19. Illustration of the flow control at the inlet of Seine-Aval WWTP with the SCORE system. The curves represent the average daily flow variation without control (green curve), and the improvement of the regulation obtained between 1992 and 1994 (other curves)

The curve below (Figure 20) shows the current flow control with MAGES in dry conditions. The steady flow is required by the operator of Seine-Aval WWTP.

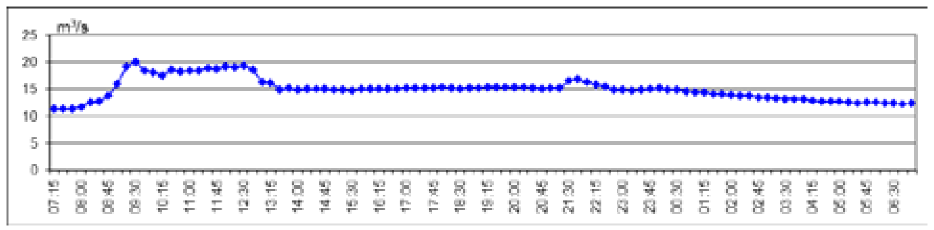

Figure 20. Example of flow remote control obtained at Seine-Aval inlet with MAGES in dry weather condition – (02/07/2018)

In 1989, following local protests, it was decided not to increase the capacity of Seine-Aval as was originally planned. This decision led to the development of a new sanitation master plan that was approved in 1997. This scheme introduced three important evolutions:

1. Downsizing Seine-Aval capacity to 1.5 Mm^3/d instead of 2.7 Mm^3/d as was originally planned. This led to a new distribution of sewage treatment capacities on SIAAP's territory.
2. Stormwater pollution control due to combined sewer overflows. The master plan was designed with the objective to avoid untreated CSOs spillage for a return period of less than 6 months. With this in view, the construction of a total stormwater storage capacity of 1,693,000 m^3 was planned.
3. Implementation of a real-time control system of SIAAP effluents. The studies of the time showed that a real-time control system would allow the reduction of 500 000 m^3 in discharges from sanitation system during heavy rains.

CASE STUDIES
INTEGRATED SMART WATER MANAGEMENT OF SANITATION SYSTEM IN THE GREATER PARIS REGION

3.3 MAGES's objectives

In this context, in 2001, the SIAAP launched with the active collaboration of all its partners (*départements*, treatment plant operators and Water Agency) the construction of a dynamic management support tool of its sanitation system, called MAGES. This system aims to meet three main objectives:

1. Global and shared knowledge of the sanitation system. To satisfy this objective, the operators have pooled the data they use for the management of their works through a data exchange system: the EDEN system (Environmental Data Exchange). EDEN allows the exchange and centralization of the measurements and the current state of the works.
2. The prediction of the operation of the sanitation system in a stable configuration. The aim is to provide each operator with a forecast of flow capacity of the sewage transport (collection) system and storage works and flow arriving at each WWTP, with a forecasting horizon of 24 hours in dry weather and 6 hours in rainy weather.
3. Assistance for the management of the sanitation system to optimize the use of the structures during the rainy episodes.

3.4 The development process

On this basis, but also thanks to the experience of SCORE and the other *départements* of the Paris region, SIAAP launched SCORE's evolution project towards a system integrating all the SIAAP networks by opening and extending it to equivalent systems of its partners.

It began with studies and *interdépartemental* working groups (SIAAP, *départements* and Water Agency) aimed at pooling knowledge about the structure and operation of the network. This stage was the occasion for establishing in-depth and intense exchanges between the stakeholders. The studies were followed by developments of the existing SCORE system. This system allowed the supervision of the flow condition (water level and speed) on the entire SIAAP network as well as the remote control of the control devices. In addition, the EDEN (Environmental Data Exchange) system has been developed to enable network supervision centers in the core zone and SIAAP to share data in real-time. At this stage, SIAAP had knowledge of the real-time structure and operation of its network and upstream departmental networks. It had tools for control and control of the network devices Flow management could therefore be implemented operationally from remote management centers. However, given the complexity of the network, a management support system seemed to be essential to optimize the use of the means implemented.

Given the very innovative nature of the management assistance tool to be put in place with the uncertainties on the results and taking into account the obligation of result, the second step was to launch a kind of contest. According to the French Public Procurement Code, two '*marché de définition*' or definition studies with two consultant consortia were selected in January 2004.

The study contracts were divided into three phases:

1. Modeling
   The objective of the first phase of the study, known as modeling, was to develop a software model to reproduce and then predict, using measurement data (hydraulic, rainfall) and various information (positions of moving parts, availability of works, etc.), the evolution of various variables that can be used for the management of structures.
2. Decision Support Tool
   The second phase involved the study of a decision support tool. It had to rely on the modeling effort of the first phase and the methods proposed by the candidate. The main result of this phase was a software model which, fed by the same type of data as the first model, was to provide management instructions that could be used by the different operators of *départemental* and *interdépartemental* sanitation works.

3. Tender Document
   The final phase was the drafting of the tender document[9]: especially the detailed requirements specification for the creation and full implementation of the MAGES forecasting and decision support tool, and the drafting of an offer to this tender document.

These definition studies began on April 1, 2004 and ended in October 2005 with the submission by each incumbent of the products from Phase 3; the tender document and the technical and financial offer for the development of the tool. Two approaches were proposed by the candidates: one proposed a solution based on a stochastic modeling approach while the other was based on a deterministic modeling of all the processes from runoff to hydraulic transport. The solution based on a deterministic model was chosen because it was considered more understandable and manageable in its adaptations and evolutions by the operating teams. The realization of this project was led by the consortium constituted by the companies *Eau et Force* (a SUEZ subsidiary) and *SATELEC*.

This led to the launch of the MAGES project, which is the core of the real-time control system. The aim was to put a forecast model of the network states and a management aid system at the disposal of the operators of SIAAP and the departments of the near suburbs of Paris. This system proposes orders on the control devices in order to reduce spills in the Seine and Marne, and to optimize treatments.

The contract, started in April 2006, consisted in the extension and the implementation for the operation of the software model realised in the definition study. This included:
- the design, production, installation, commissioning of operating tools (hardware, software) on all operating sites for real-time uses (management scenario proposals) and deferred time (simulation of past situations, integration of new system documentations, training, testing of different scenarios);
- setting up these tools in accordance with the current situation of the territory managed by the SIAAP and partners, and with the specific needs of each operator;
- the development of the central control station: SAPHYR PC;
- the training of future MAGES users.

3.5 The technical solution

3.5.1 General principles

MAGES relies on real-time deterministic modeling of transport and storage structures with 23,000 calculation points coupled with an optimization process for searching the management scenario. This modeling takes into account the following inputs based on an intensive data sharing network (see Figure 21, Figure 22):
- dry weather sewage flow inputs;
- measured and forecast rainfall inputs;
- field measures data with a set of more than 2,000 sensors;
- physical changes to the sanitation system. These could be related to maintenance works or incidents inherent in the operation of any sanitation system.

9. In French : dossier de consultation des entreprises

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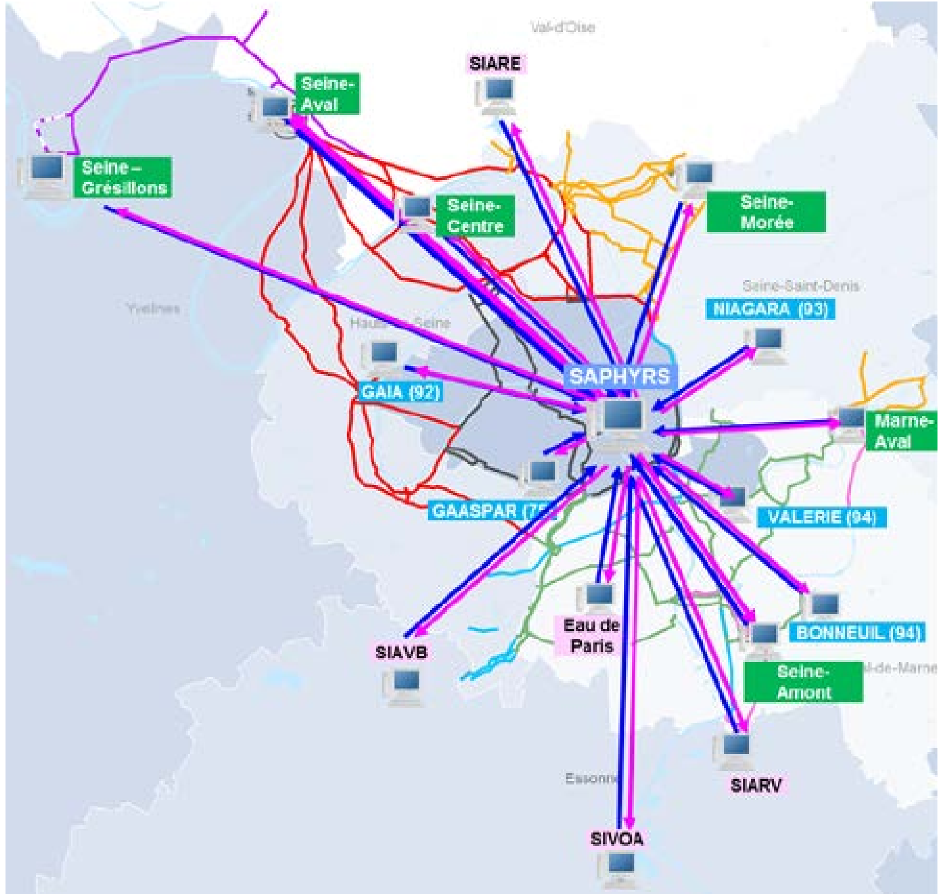

Figure 21. Main data transfers between SAPHYR control room and MAGES with WWTPs (green) SIAAP operator members (blue) and outside operators (pink)

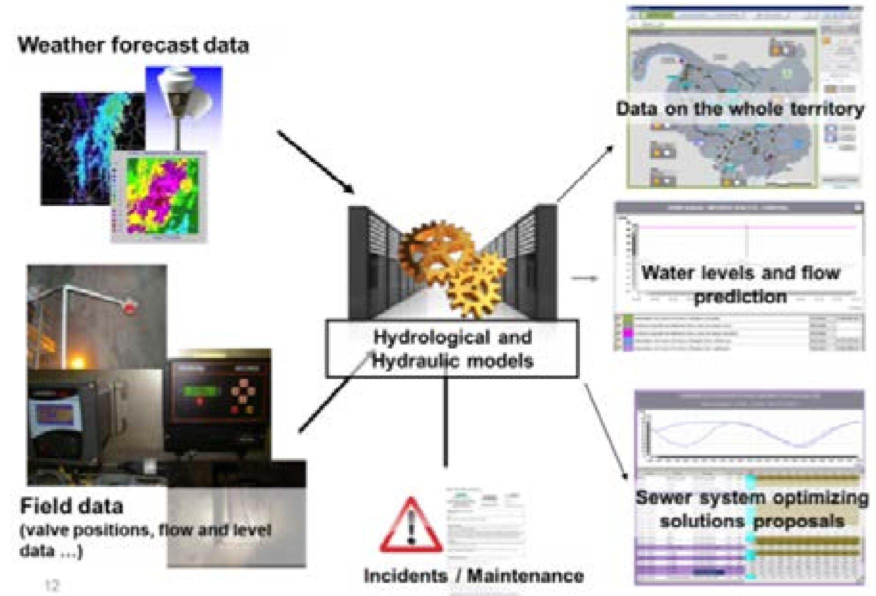

Figure 22. Schematic of data and MAGES output processing operations

A MAGES treatment cycle updates every five minutes to show:

- Identification of the current state of the system:
  - the measurements collected in real-time, after following a validation process,
  - these measurements are also used to update the models (position of regulators, filling of basins, etc.),
  - the simulation of the state of the network carried out with the detailed hydraulic model. This simulation provides a consistent state of the system by completing the valid measurements with the results from the modeling. Thus, each operator has at the same time a synthetic, comprehensive and complete vision configuration and hydraulic status of the sewerage network, e.g. heights, flow rates, discharged flows, volumes stored, volumes treated, etc.

- Prediction of future trends.
  The MAGES system provides the expected state of the system by integrating the effect of the rain forecasts. It is based on the detailed hydraulic model: flow rates and water levels are estimated assuming that the network configuration (valve position, pumping rates) is unchanged over the prediction horizon, except for works which have a local regulation, which is taken into account in the forecast. The hydraulic status (flows and heights) is then displayed for around 400 key points along the network, with a horizon of 24 hours in dry weather, and 6 hours in rainy weather.

- Determination of the optimized management scenario.
  A linear model based on simplified hydraulic and hydrological equations calculates a large number of simulations in a few minutes, the results of which contribute to the creation of an optimization problem. This optimization problem is subject to a solver that minimizes the cost of an 'objective' function. It is the parameters of this objective function that set the priorities such as limiting spills to the different weirs, the priority of use of the different available storage volumes, or the operating time in the rainy season configuration of the treatment plants.
  The simplified model is recalibrated with the detailed model at each 15-minute computation cycle. This solution ensures rapid calculations and convergence of the optimization problem while ensuring realistic and stable solutions, whatever the weather conditions. The scenario is presented in the form of objective flows calculated by the simplified model for 26 key points along the network, selected for their management potential. These flow-objectives are also translated in the form of instructions for the ~50 main control structures (valves, pumping group, etc.) of the sanitation system. They are presented to the operators as valve positions, flow or water level instructions, depending on the management mode of the structure.

- Prediction of the optimal trend situation.
  The instructions for the main structures obtained in the previous step are injected into the detailed hydraulic model to provide the state of the system in the event that the proposed instructions are actually applied.

There are three 'objective' functions, corresponding to the three management strategies that have been set in MAGES. These strategies include:

1. The 'long-term dry-weather strategy', aiming to smooth overall contributions to WWTP while not increasing the risk of spills.
2. The 'overflow rain conditions' strategy aims at minimizing spills without increasing the risk of floods by overflow during medium to heavy rains. By anticipating the emptying of the collectors, it optimizes the treatment at the WWTP and the storage capacities in the basin and network.

3) The 'rain overflow time' strategy is designed for heavy rains, to fight primarily against the risk of overflow of the network on the roadway. All the outlets are then used to relieve the network.

Even if there are automated local control devices, the operator is able to act directly on 160 remote control devices such as valves or pumping stations (see Figure 23).

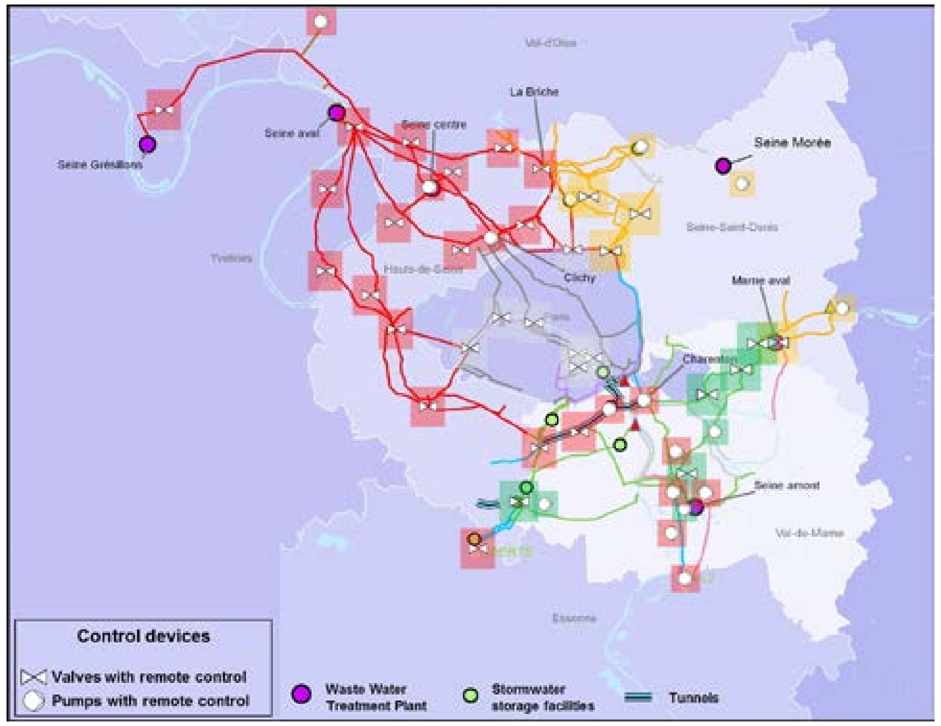

Figure 23. Main remote control devices. (Colour code for sewers refers to the operator: red for SIAAP, grey for Paris, orange for Seine-Saint-Denis, green for Val-de-Marne)

3.5.2 Current state and trend prediction by detailed modeling

MAGES relies on a deterministic modeling[10] of the urban water cycle, from the hydrology of the perimeter (transformation of the rain heights into runoff water to the network) to the hydraulics of the structuring network of the sanitation system. Real-time accurate reproduction by a detailed model of dry and rainy weather inputs, network configuration and meteorology conditions feed into the results of the modeling. Taking them into account is a real technical challenge whose main characteristics are presented below.

3.5.3 Dry weather flow assessment

The MAGES perimeter was divided into 60 input sectors, which are broken down throughout the network by 153 sewer inflow points. In order to reproduce the weekly and monthly fluctuations in wastewater and the seasonal variations in permanent infiltration water inflows that have been shown to correlate directly with groundwater levels, a process of recalibration of dry weather flow has been developed in MAGES.

On each catchment area, feed hydrographs of wastewater and infiltration water were constructed from the archived data. For the real-time adjustment of these hydrographs, the

10. Deterministic modelling in this case refers to all of the physical process involved in the flow calculation at each point of the network relying on mathematical formula to describe the hydraulic conditions such as slope, shape of sewer, sewer material with Strickler coefficient, hydraulic formula for each kind of devices, etc.

simplifying hypothesis adopted is that the global volume of dry-weather inputs modeled for the current day is best approximated by the volume measured at the treatment plants for the last known day of dry weather. A statistical analysis carried out with three years of self-monitoring data of the WWTP showed that the total volume of inputs calculated from the measurement of the last known day's contribution is a good estimate, within a confidence interval. +/- 11%, for 95% of cases. This method thus ensures that changes in dry weather production are taken into account correctly, in particular seasonal variations in infiltration water and wastewater inputs (especially during the summer holidays period), as well as inter-annual changes in wastewater production, particularly related to the changes in consumption of drinking and non-drinking water.

The adjustment variable used is the total daily flux of nitrogenous materials (organic nitrogen and ammonia, expressed in TKN) measured in the WWTP, directly correlated to the volumes of wastewater produced over the catchment area. The overall infiltration volume is deducted from the difference between the input volume and the wastewater volume. Finally, the correlations between the total volume of wastewater and infiltration water and the values per catchment of these two quantities make it possible to adjust daily hydrographs for each input basin.

3.5.4 Assessment of stormwater inputs

In order to have an accurate cartography of the precipitation data, the SIAAP use the CALAMAR® model. From the images of the meteorological radar of Trappes (78), distributed by METEOFRANCE and measurements of the 80 rain gauges operated by the four constituent *départements* of SIAAP, CALAMAR provides data at 5-minute intervals with the spatial distribution of rainfall over the covered area, and a resolution of 1 km^2. In addition to this measure, the 2-hour forecast, at 5 minutes intervals, is used as the MAGES input variable. The data for past and projected precipitation is then mapped onto the territory using radar images, divided into 1200 watersheds, representing a total active surface of 28 000 hectares. The volumes are then distributed to the 388 sewer inflow points in the hydraulic model (among which there are 153 points of dry weather inflow points).

3.5.5 Metrology

Metrology is an essential component of MAGES: it builds an understanding of the current state of the sanitation system and updates the models used for the elaboration of the trend and optimized situation. Metrology is a set of more than 2,000 sensors corresponding to flow, level, valve position, level or flow rate measurements. A measurement validation process based on several complementary methods was set up on each of the measurement points to ensure the quality of the input data of the system. In addition to these systematic and automatic validation methods, authorized operators have the possibility to intervene to inhibit the measurement of a given sensor, or even correct the value if they know it.

3.5.6 The detailed modeling

The modeling tools are the METE-EAU® software package for the hydrology of the upstream zones of the network and HYDRANET® for the hydraulic modeling, both developed by the company Hydratec. These tools have been adapted to meet the constraints of fast execution of calculation cycles and robustness of operation for operational use. Indeed, the modeling implemented extends over 500km of main sewers, modeled by 3 113 'user nodes' (and translated into 23 000 computation nodes). 150 management stations (basins, valves, pumping) were modeled, integrating the automated local management rules for existing ones.

To satisfy the execution time constraint (approximately 3 minutes for a 24-hour simulation), several processes for optimizing the calculation time have been implemented, notably the 'hot restart' of the results of the previous calculation cycle and a division into 5 interconnected sub-models. Calculations are performed sequentially by sub-models according to upstream - downstream logical tree (see Figure 24).

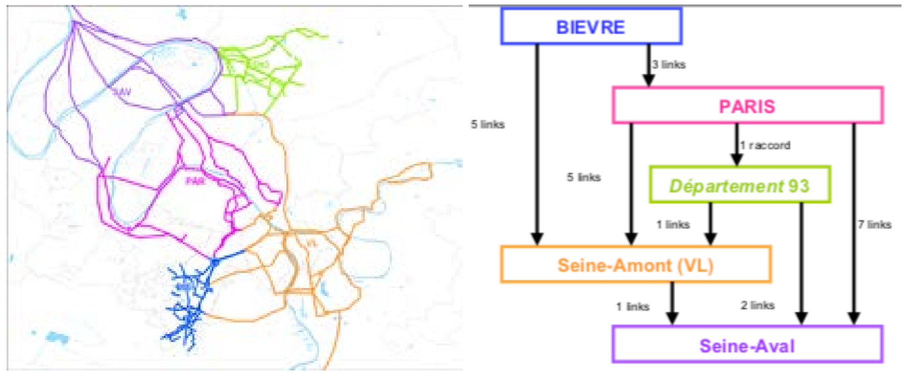

Figure 24. The five hydraulic sub-models and their links

3.5.7 The MAGES update process

In order to guarantee the coherence and the reliability of the results calculated by MAGES compared to the field reality, the model is updated according to a cycle of 5 minutes for all the information influencing the result of the predictive modeling. During this process, the following inputs are taken into account: the measurement and the rain forecast, the measurements (positions, instructions, flows) and the configuration of the works which result from the predictable and known maintenance works, but also from the interventions and incidents which are inherent in the operation of any sanitation system.

A first update function is performed on the control and storage structures, at each 5-minute cycle, using the previously validated measurements.

A second function of updating has been developed to take into account the operations of works in maintenance. The works programmed several months in advance are communicated to the model via a specific interface, as well as their translation for all that concerns the routing of inputs or the modification of the management rules of a control device. Once the operator has validated the beginning of the work, the model automatically updates itself on these new configurations of works, as of the following simulation cycle.

This update is also applied for any incident that occurs on the network, such as a set of maneuvers routing effluent following a WWTP operating problem.

Finally, in the absence of the updated data, the model reproduces an operating dynamic management based on the rules that are routinely applied by the operator for each local management station. The result is a baseline scenario, which provides consistent and credible results in a fallback situation that is when none of the update or registration data normally provided by metrology is available.

3.5.8 The optimised scenario construction

The optimisation aspect of MAGES includes an optimiser, which minimizes the cost of a 'multi-objective' function and a simplified model, quasi-linear, used to assess the cost of this 'multi-objective' function in different configurations of the main devices for the network management.

The 'multi-objective' function reflects the cost of spills, overflows, storage in the works, and the use of the stormwater pollution treatment systems. The room for maneuvering that this function allows are the saturation of the dry and rainy weather treatment capacity of the WWTP, the filling of the storage facilities, the use of the interconnected sewage network and, of course, the use of different combined sewer overflow devices.

The optimiser used is the MINOS solver developed by Stanford University. The simplified modeling and control of this optimization are carried out with the CSoft software, developed and distributed at that time by the company BPR-CSO, It is a model of the input-output type, able to calculate the flow, to reproduce the flow rate in the pipes and to explicitly satisfy the continuity equation at the nodes. The parameters of this model are calibrated from the validated measures where they are available, supplemented by the results of the detailed model for the other points (in particular those which are not instrumented).

The optimization module builds the optimization problem for the fifty key piloting devices that have been selected. The result consists of the optimal instructions that are proposed for each of these control devices, over a control horizon of 6 hours or 24 hours.

The automatic construction module of the problem formats the equations and inequality factors, which need to be optimised to solve the problem. The equations reflect the respect of material balances at the management stations and the hydraulic constraints (i.e. flow rates to be respected). The inequality factors represent the intervals to be respected (i.e. minimum flow and maximum flow at the WWTP). This module uses the results of online calibration to construct dynamic flow equations.

This same module then establishes the multi-objective function using the weights and penalties that are specific to the strategy in use. These 'objective' functions are stated above (see section 3.5.1).

In order to compare the gains of the optimized scenario with the trend situation on the basis of the same detailed simulation tool, all the instructions proposed for the optimized scenario are incorporated into the detailed model. Thus, the operator is able to judge the impact and relevance of these instructions, comparing their effects to the current management. The calculation resulting from the application of these instructions corresponds to the 'optimized trend scenario'.

3.5.9 The non-real-time mode

Besides the real-time system, there is a non-real-time mode. This mode allows several possibilities:

- to work on past events in order to study these events and learn from experience;
- to make studies for maintenance shutdown. This allows managers to study the best scenario which aims to avoid spillages or to reduce them when there is no other option;
- to test different operation scenarios;
- for training sessions.

This non-real-time mode is also necessary to replay past situations because the system keeps all the real-time results of the last three months in its memory. Beyond this limit, the non-real-time mode is used to 'replay' the situation with all that data which are all stored in the data base.

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3.6 MAGES, an operations tool

3.6.1 Simplified architecture and processing cycle

The architecture of the system is based on the principle of modularity. The detailed model (METE-EAU and HYDRANET), the optimizer (CSoft with MINOS), the Human Machine Interface (HMI), the database where measurements and results are stored, the reception of meteorological data and metrology constitute many independent modules that interact with each other through the supervisor (controller) system.

Figure 25 illustrates the general IT architecture of the tool.

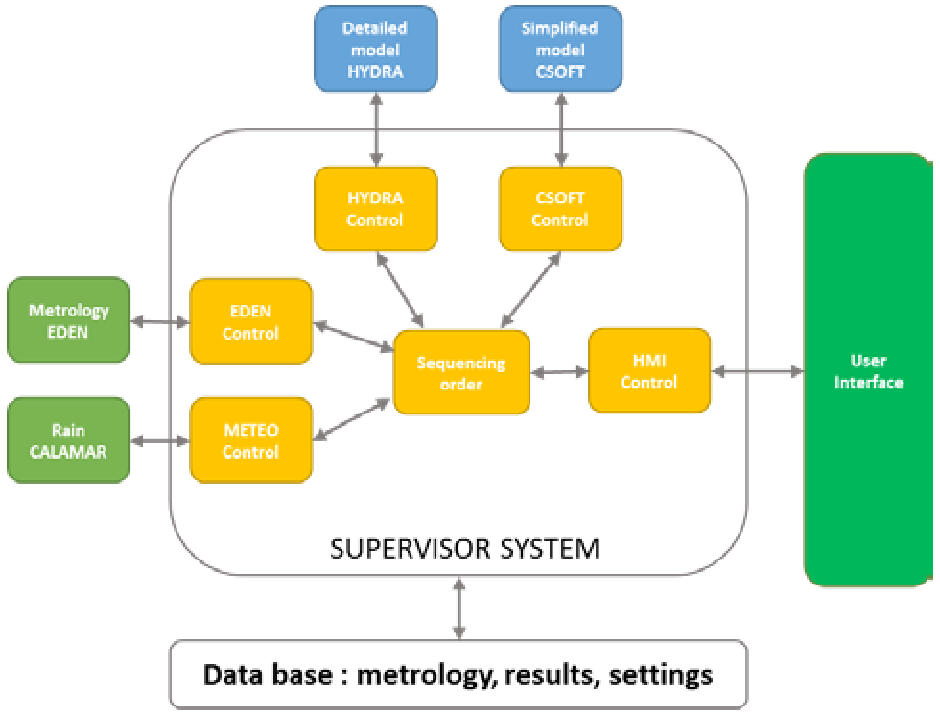

Figure 25. MAGES general computer architecture

The supervisor (controller) system was developed as part of the MAGES project, with the user interface. The supervisor is sequencing the exchanges between all the other modules. Its operation stems from the explanations provided previously:

- On a time step of five minutes, it retrieves and filters metrology and meteorology data, then updates the detailed model to calculate the current situation;
- In a quarter hour, it successively launches the detailed predictive model, the simplified model that produces the optimal set points, and then again the detailed predictive model. This results in the displays of:
    - The reference trend situation,
    - The optimum management scenario,
    - The trend optimised situation.

Figure 26 summarizes the nominal processing cycle of MAGES.

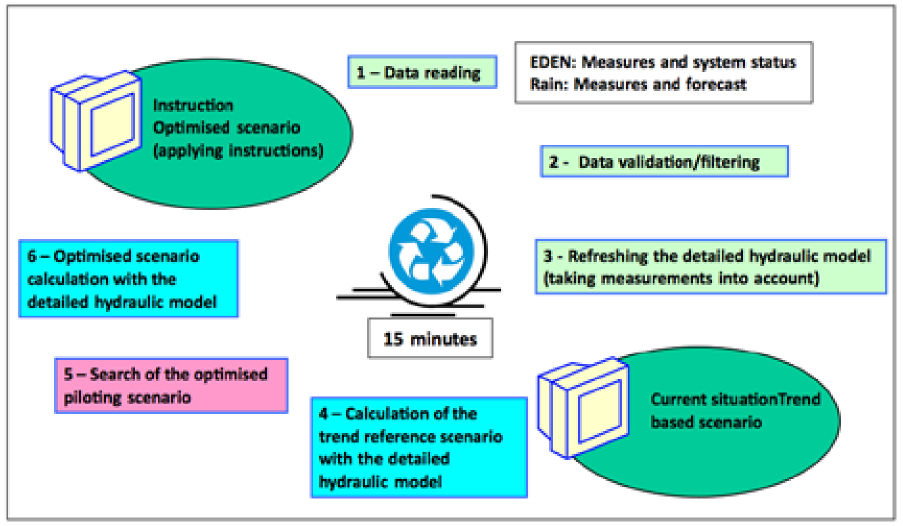

Figure 26. Simplified processing diagram

The hardware and software IT infrastructure has been implemented redundantly to ensure a high level of availability.

Beyond the various applications needed for configuration that have been delivered to the administrators of MAGES, two main applications are intended for users:

- The Human-Machine Interface for decision making application, which provides access to all the features mentioned in this article (current situation, baseline trend scenario and optimized trend scenario);
- The 'Maintenance shutdown' application, which provides information on planned shutdowns.

MAGES is accessible under the same conditions from the dedicated computers that are installed in the operators' control rooms, and from the computers that are located inside the SIAAP computer network. An Internet connection also allows the duty staff to access the same information from outside their office.

3.6.2 A global and shared vision of the system

The coherence of all the data provides a global and shared vision of the operation of the sanitation system. It places operators in a global management framework by providing them with information that goes beyond their strict management scope. With the current situation operators located upstream have the opportunity to know the impact of their actions on the downstream network.

Figure 27 provides a screenshot showing the entire perimeter of MAGES. It includes the structural collectors, the six WWTP and their operation setting (dry or rainy weather) and the piloting stations that are receiving instructions. Thematic indicators are also available such as the measurement and rain forecast, dry and rainy weather hydrological inputs, the stored volumes and the storage rates in the different sewers, the flows transited at the key points of the network, the flow directions of the main flow rates as well as the discharged flows at the 112 modeled sewer overflows. Each of these indicators is presented in the form of on curve (see Figure 28) calculated on the past compared with the observation (which can vary from 0h to 72h) and a forecast on the control horizon, which is 6h in rainy condition or 24h in dry condition.

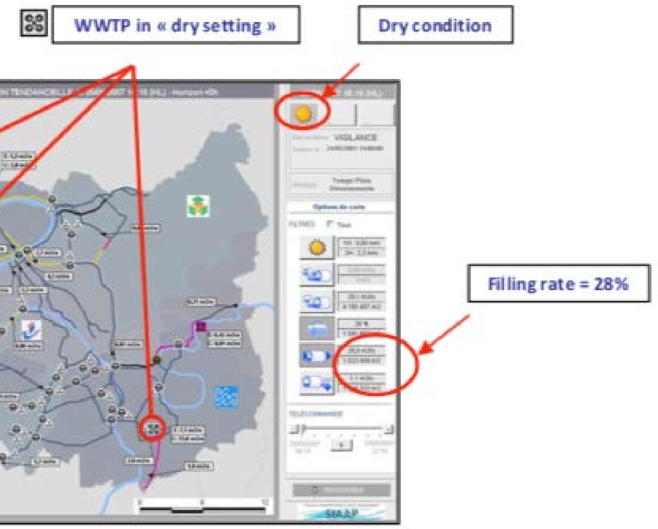

Figure 27. Global overview of the system and thematic indicators

This general vision can be zoomed in on each of five major input areas (Figure29). Each control-station has a synoptic window that describes its overall configuration using a symbolism common to all operators. These synoptic windows also constitute a portal to access local information.

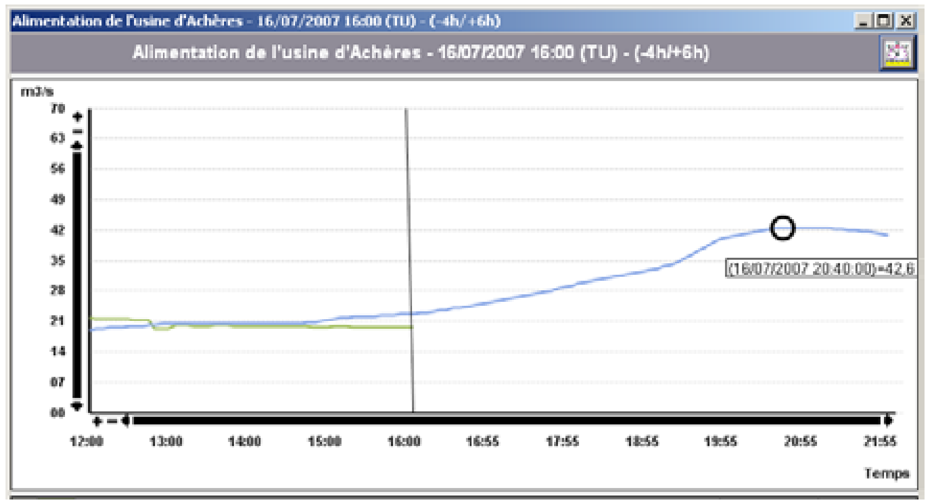

Figure 28. Forecast of a pic flow of 42.6 m³/s at 20:40 at Seine-Aval WWTP at 16:00
(green curve: measurement, blue curve: modelling)

3.6.3 The forecast and the optimisation

The trend situation for operators is predicted by the forecast of very high levels of water or flow in the network (see Figure 29), the prediction of the location of spills, the filling rates in the sewers and the operation during rainy weather of the treatment plants over a horizon that varies between 2 and 6 hours.

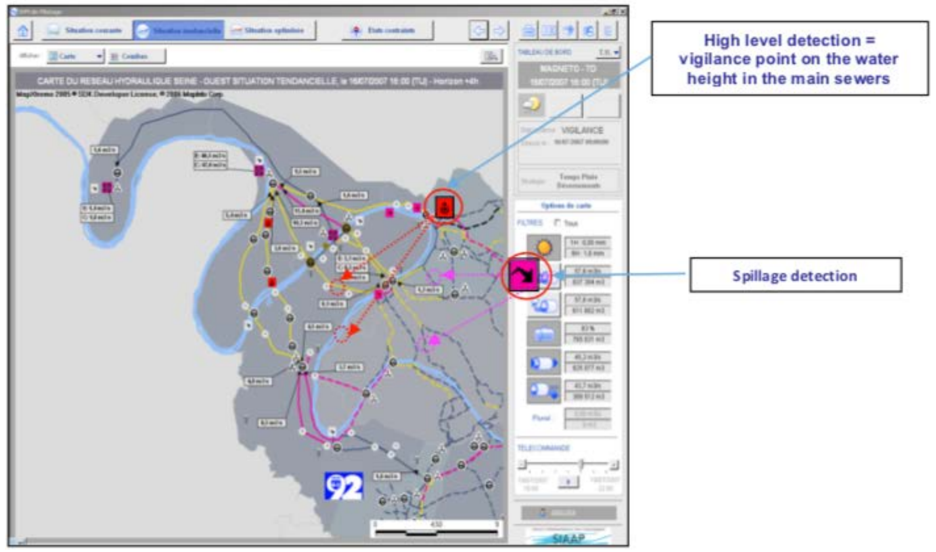

Figure 29. At 16:00, high levels anticipation of 4h, dumping points and storage rates in the Western network, scheduled for 20:00

All information in the previous figure is also available in the form of predictive curves for the various important locations of the sanitation system such as the flows entering the WWTP, entering and exciting the storages basins, arriving at the interconnection points, on the CSOs, etc. (see Figure 30).

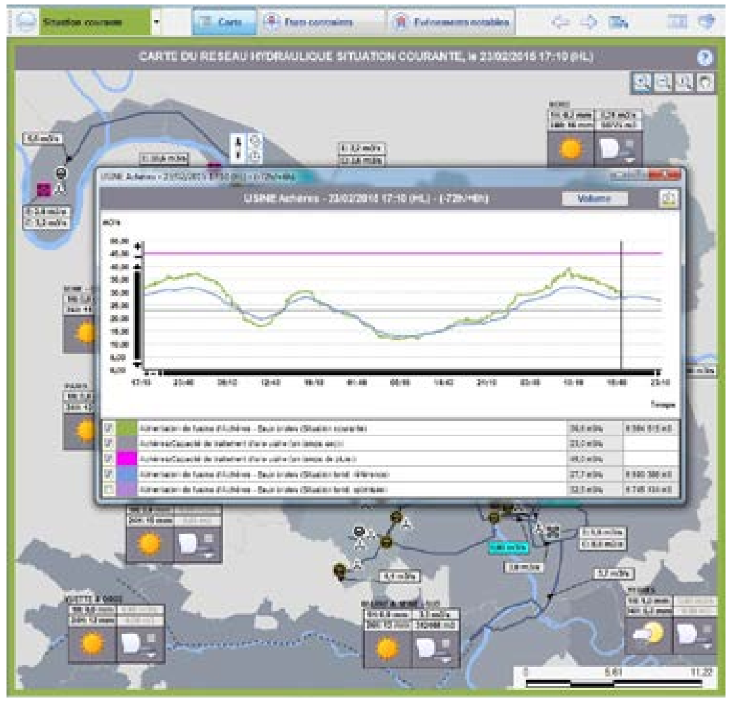

Figure 30. Screen shot of flow prediction at Seine-Aval WWTP planned (green curve: measurement, blue curve: model)

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3.6.4 Conclusion

The technical solutions implemented for the construction of MAGES made it possible to satisfy the objectives of global and shared knowledge of the sanitation systems of the Paris region for different actors. This technological advance will be accompanied by profound changes in the operating methods of water treatment plants and networks. Indeed, with MAGES, the flow management in the Paris region is based on weather conditions and operating constraints, technicians are then enable to make responsive and concerted decisions. In addition, the decision criteria for the management of the network are built on the scale of the region and no longer only at the local level.

Beyond its real-time use, MAGES is also a tool for studying and assisting in the design and operation of new works, in order to make the most of available processing capabilities by optimizing volumes of existing or projected storage facilities.

3.7 Enablers and barriers

The implementation of the MAGES project was made possible because of converging opportunities and technical reasons:

- Paris region sanitation operators had a long experience with real-time control systems in sanitation. Their development and implementation started in the mid-1980s. In the early 1990s, each SIAAP member and the SIAAP itself were running a RTC system. This led to a shared technical culture background;
- The implementation of a global RTC system at SIAAP's was one of the main outcomes of the 1997's sanitation master plan;
- SIAAP's willingness to implement this outcome of the sanitation master plan was a key point;
- The financial and political support of the Seine-Normandy Water Agency (AESN) has also been a very important factor. The Water Agency funded this project with subsidies that covered 40% of costs and a loan of 20% with a zero rate. In addition to these funds, the Ile-de-France Région supported the project with 20% of subsidies.

Rather than barriers, it would be more appropriate to speak about resistance. When the project started, there was a slight fear about how the SIAAP would exert its leadership on this project. After the first working meetings, the resistance progressively disappeared, helped by the stimulating challenge that the project represented which the team was interested to solve and also by the commitment of leaders of each partner. After the first phase of slight resistance, each learned from the other and then a climate of confidence took place through an important work dedicated to the conception of a data dictionary and the follow up of the '*marché de definition*' or definition studies (see section 3.4). One other reason for the success of the project was that each partner kept tis own RTC system (see section 5).

3.8 Achievement and impacts: The contributions of MAGES and smart management

The development of MAGES accompanied a period of major evolution of the sanitation system in the Paris region because at the same time the SIAAP facilities were completing a profound transformation, downsizing the *Seine-Aval* WWTP (See 1.2. and 3.2.1).

At the end of the 1990s, the SIAAP had 3 large WWTP: *Seine-Aval*, *Seine-Amont* and *Seine-Centre*, *Marne-Aval* with smaller stakes. The SIAAP was just coming out of decades of chronic insufficient treatment capacity, the margins of management were low and the management was very static. The following decade led to a complete change of scenery linked to the political decision to reduce the size of the historic treatment plant: *Seine-Aval* which, as it is explained; must go from 2.1 Mm^3/d to 1.5 Mm^3/d involving the construction of new WWTPs in compensation. This evolution of the treatment system is also accompanied by a major transformation of the southeastern part of its transportation system intended to feed the *Seine-Amont* treatment plant. New connections and stormwater storage facilities with a capacity of 580,000 m^3 were created.

Thus the SIAAP went from a situation of a shortage of treatment capacity to a completely new situation with room for maneuvering. It is in this context that the dynamic flow management project comes into play. The commissioning of MAGES has brought a radically new vision because this remote management, assisted by powerful processing capacity and interconnected network, allows modification of the distribution of flows between the WWTP with much more flexibility and a global vision. The commissioning of MAGES greatly facilitated the assimilation of the changes that had just occurred. From static and local, the management has become dynamic and global.

Progressively the Flow Management Service of the Networks Department, manager of MAGES and the SAPHYRS control room, thanks to the knowledge learned on a daily basis, has become a 'control tower' with a global vision of the operation of the whole 'WWTP-networks'.

MAGES has progressively led to the establishment of procedures and the modification of organizations. The dialogue between WWTP has developed, as has the dialogue between the flow manager and the WWTP operators. The vision of the sanitation system has been radically changed.

3.8.1 Various forecast horizons

One of the peculiarities of MAGES and its developments is that it allows vision and use at different time-scales:

- 24 hours: this is the current real-time operation with the sharing of data, instructions to optimize the solicitation of transport, storage and treatment works, taking into account the recent past of dry weather or not;
- 1 - 10 days: this is the current operating horizon with a detailed and optimized programming of the maintenance operations, giving rise to a provisional bulletin of conduct of the exploitation;
- 1 to a few months: this horizon is that of feedback based on the 'Non-real-time' function of MAGES. It allows the feedback of experiences on past situations but also special studies such as the maintenance operations programming or exercise simulations;
- 1 - 3 years: it is the time of the multi-year programming of the shutdown operations and specific studies for particular operations.

Related to these times-scales, there are several outputs for the sanitation system operation. The following paragraphs detail some of these uses.

3.8.2 A shared and global vision

The first objective of providing a global and shared vision has been achieved since the commissioning of MAGES with the consistency of all the data that provides the overall vision of the operation of the sanitation system. It places operators in a global management framework by providing them with information that goes beyond their strict management scope.

The shared vision made it possible to set up a real cooperation of the different actors, which are part of a process of continuous improvement of the operation.

This shared vision materialized concretely, but the effects of transfers of water with sometimes very different qualities accelerated the process of sharing information. Today, bimonthly meetings bringing together plant and network operators have been set up to ensure the analysis of past situations, the optimization of operations, the sharing of experiences, and thus getting into a process of continuous improvement of the operations, based on the data provided by the MAGES tool. These exchanges have become essential to the proper functioning of the sanitation system.

3.8.3 Optimizing real-time operation

Based on the prediction of dry and wet weather inputs, MAGES provides in real-time, at all points in the network, the flows and water heights at the entrance of the WWTPs and at the characteristic points of the transport network.

The real-time knowledge of hydrographs with an optimized forecast over the next 6 hours provides relevant and essential information for operators to make the necessary decisions on the conduct of their installations. This predictive management makes it possible to better anticipate *a)* the start-up of the specific stormwater pollution treatment facilities or to change WWTP configuration from dry weather to rainy conditions, *b)* the regulation of the flow rate on the treatment units to avoid saturating them with a peak of pollutant load likely to exceed the design capacity of the treatment units, *c)* the coordination of the phases of storage and emptying of different reservoirs and tunnels tanks.

3.8.4 Forecast Bulletins for the operation of Networks and WWTPs

Faced with the findings of strong interactions between WWTPs and networks for efficient management, a provisional bulletin for the management of the SIAAP networks and WWTPs is drawn up each week. It is established in liaison with WWTPs and network operators and is distributed to all operational departments and functional departments responsible for operating reviews and monitoring of the natural environment.

This bulletin provides summary information on the situation of the availability of each of the WWTPs and networks according to the works and incidents. This situation is given for the current day, a forecast of the contributions and the distribution of flows for the next 10 days and taking into account the annual shutdown program for the next 3 months. This forecast is based on the non-real-time version of MAGES. The information is correlated with data from the natural environment (flow and temperature of the Seine) as well as trends for rain over the upcoming 10 days, and can if necessary be adapted to limit the impact on the environment. A synthetic map indicates the network shutdowns for maintenance or reduction of the capacity of the WWTPs. The situation regarding the H_2S and CH_4 gas risks in the networks is also described.

3.8.5 An adapted flow management for Seine-Aval WWTP

Among the 6 WWTPs, *Seine-Aval* plays a major role its capacity and location within the network. It is frequently used to help other WWTPs. The opposite is less true because only two plants can contribute to reducing, in limited proportions, the incoming pollutant loads on *Seine-Aval.*

Low flow rates are critical for this facility originally designed to handle daily volumes equal to or greater than 2.1 Mm^3/d. In summer, flow rates sometimes drop below 0.8 Mm^3/d and flow rates of less than 10 m^3/s are problematic. Also an operational procedure for real-time regulation of flow rates to avoid going below this threshold has been put in place. It relies on a transfer of water from the *Seine-Centre* and *Seine-Grésillons* plants supplemented by storage in the emissaries to support the night flow.

The main sewers that feed the *Seine-Aval* WWTP were originally designed to drive 2.7 Mm^3/d. With the reduction in capacity, the flow rates have become low making them susceptible to deposits. The recovery of these deposits during heavy rains pose operating problems that can lead to unacceptable exceedances of standards. To limit these risks, the operator requests a specific regulation with a rise in flow per stage of 5 m^3/s in time step of 15 mn allowing him to change configuration: physicochemical treatment of the stormwater in place of phosphorus.

3.8.6 Shutdown management for works

The provisional management of shutdown of facilities is a major issue for operators. Major construction and maintenance operations on the WWTPs, cleaning, inspection or rehabilitation of the wastewater transportation network are scheduled each year for periods sometimes of several months. Figures 31 and 32 show the summary of location, kind and duration for maintenance and duration of shutdowns.

A multi-year program is carried out based on the non-real-time version of MAGES. A procedure is used to develop the shutdown program for the following year submitted to the water police authority for approval after assessing the impact on water bodies. This coordination is essential to ensure that the program does not present major incompatibilities in terms of operation and unacceptable impacts by the receiving environment.

MAGES is one of the major tools for assessing the impact of water diversion from watersheds whose characteristics of domestic and industrial inputs can be variable.

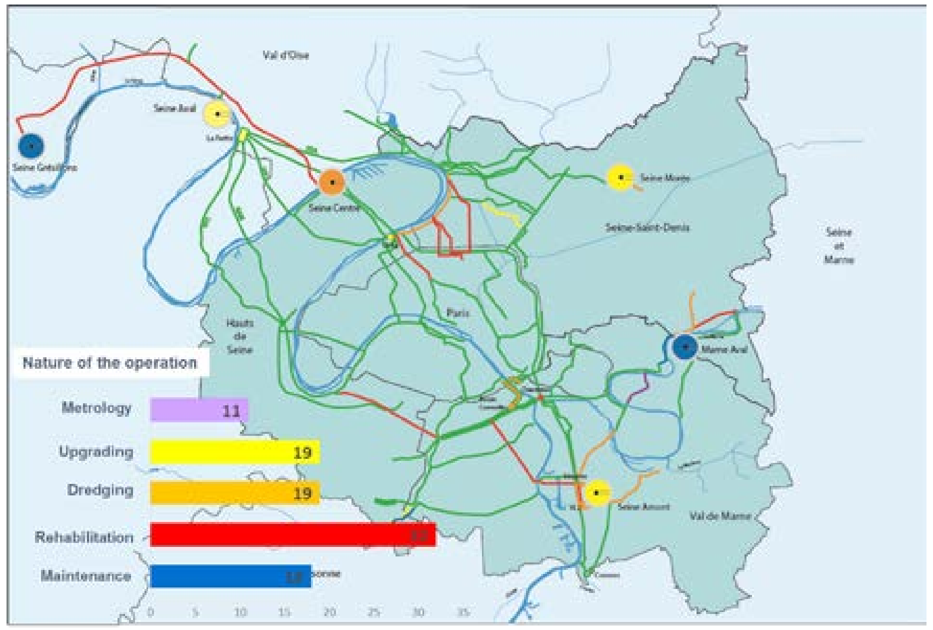

Figure 31. Location of different kind of maintenance operation (2016)

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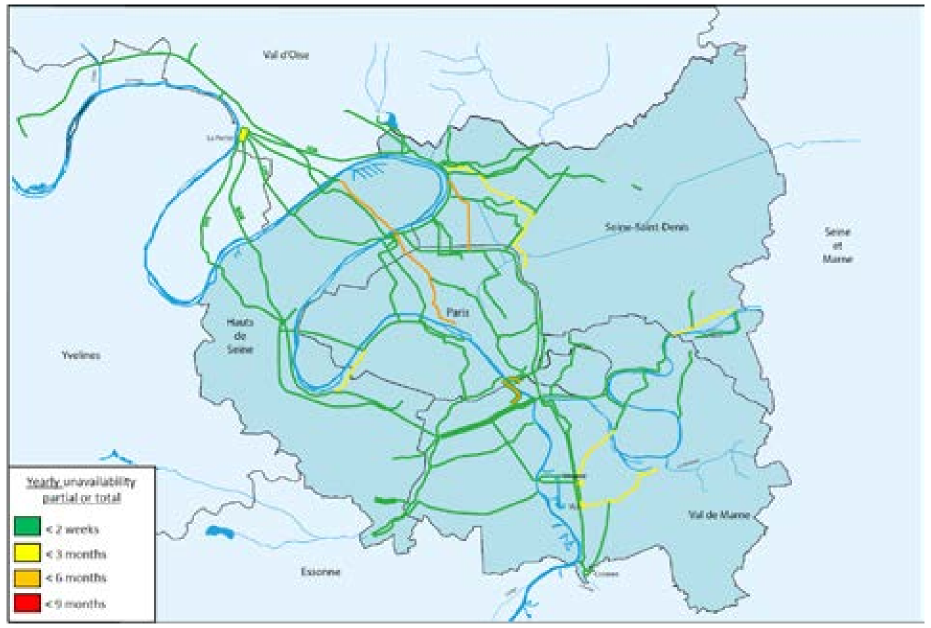

Figure 32. Duration of maintenance shutdown on the SIAAP's main sewers (2015)

3.8.7 The management of incidents

The management of all equipment malfunctions is also facilitated by the MAGES tool. The real-time updating of the characteristics of the transport, storage and treatment works of MAGES is a major asset to limit the impact of these incidents on the environment.

3.9 Cost elements

Speaking about the investment cost of the development and implementation of the whole project is quite difficult because costs take into account several topics and the system is under a continuous process of improvement and renewal of equipment such as sensors or hardware for computing system.

This project was financially supported by the Seine Normandy Water Agency and for a part of it by the Ile-de-France regional Council in the frame of a multiannual (1999 – 2009) contract for the financing of SIAAP's works. It appears in this contract as 'Dynamic flow management project' and the initial budget of €35 million covered the main initial investments related to the real-time management project (see Table 9). This same contract was for a global amount of work of €2.5 billion to improve SIAAP's sewage treatment capacity and performances, developing new sewers connections and storage facilities. This means that compared to the whole investment carried out by the SIAAP, the RTC cost for development and implementation is quite low compared to its outputs for a more efficient operation of the whole system.

Table 9. Main initial investment costs for the RTC implementation

Main contracts	Amount (non-actualized value)
Interoperable data exchange system (EDEN)	1.7 M€
Existing SCORE modernization including the new central command room, development for implementation of new facilities, networks and storage facilities, etc.	19.4 M€
Definition studies contest	4 M€
MAGES Development and implementation	8.5 M€
Miscellaneous : metrology development and improvement, complementary studies, etc.	4 M€
Total	37.6 M€

The operation of the whole system is supported by a team of 32 people and among them 16 people are involved in the rolling shifts 24 hours a day, 7 days a week

4. Links to the Sustainable Development Goals

MAGES is one of the SIAAP's tools that are in operation to fulfill the goals of the French regulation derived from the European Water Framework Directive and to optimize the operation of the system with the search of efficiency.

As stated in this section, MAGES is a smart system allowing a fine operation of the complex sanitation system that has been built over several decades. The main output is that it provides in real-time the current state of the system and the forecast both in dry or rain weather conditions. This greatly helps to adjust the operation for the best result taking into account the current conditions. In this way, MAGES contributes to reducing the impact of the Paris megacity on the receiving waters. Its future improvement and development will help to optimise the whole process and in this way will help to reduce the energy and reagents' consumption. These future improvements are explained further in the next part of this section (see section 6). By this way, MAGES helps to reach the several Sustainable Development Goals (see Table 10).

Table 10. Links to the Sustainable Development Goals

Sustainable Development Goals and Targets	
SDG 6: Clean water & sanitation **Ensure availability and sustainable management of water and sanitation for all**	
6.3	By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally
SDG 9: Resilient, sustainable and innovative infrastructure **Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation**	
9.1	Develop quality, reliable, sustainable and resilient infrastructure, including regional and trans-border infrastructure, to support economic development and human well-being, with a focus on affordable and equitable access for all
SDG 12: Sustainable consumption **Ensure sustainable consumption and production patterns**	
12.2	By 2030, achieve the sustainable management and efficient use of natural resources
SDG 13: Climate change action **Take urgent action to combat climate change and its impacts**	
13.1	Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries

Target 6.3

MAGES's contributes and will contribute more to a better management of Paris region sanitation. One of MAGES' main goals is to reduce the loads of pollutants discharged to the receiving water, especially during rain events. Several kinds of pollutants are of concern, including: reduced nitrogen, COD, micropollutants such as hydrocarbons and heavy metals.

By monitoring and adjusting the levels of these pollutants in the Seine, the SIAAP is contributing to improved sanitation at a local scale. On a global scale, the SIAAP is sharing knowledge on the technologies they have developed which help to greatly improve sanitation, providing the potential for these technologies to be replicated elsewhere in the world in the future.

Target 9.1

Performance is nothing without reliability. As a smart management tool, MAGES, already contributes to a reliable operation of the sanitation system: it helps to reduce significantly the spillage of raw wastewater, especially during shutdowns for maintenance.

By the global overview that MAGES provides to each of the operators, it enhanced the performance of the whole system and made it more adaptable to changing situations, which can be considered as enhanced resilience. It will help in the further developments to reduce energy and reagent consumption. In this way, it contributes to making the system more sustainable.

Target 12.2

The next MAGES developments will aim to reduce the energy and reagents consumption by optimizing the performances relating to the needs of the receiving waters. By doing this, the SIAAP aims to globally reduce its consumption. This is of course not the only field of natural resources management improvement.

Target 13.1

MAGES is one of SIAAP's tools to strengthen its resilience and adaptive capacity to climate problems. The recent flood events that occurred in Paris in 2016 and 2018 showed how these smart tools are relevant to manage crisis situations. Of course the global performance depends on the infrastructures' features but smart tools are helpful to optimize what you can expect from the different facilities.

In the future, the Paris region will have to adapt to a decrease of the Seine's flow related to climate change effects. The future development and improvements of MAGES (see below) are design to help to mitigate these new conditions.

5. Lessons Learned

The development and the implementation of MAGES are the result of a long process started at the beginning of the 1980's which ended in 2008 by the commissioning of this system; it means more than 20 years of investment in research and engineering in the field of real-time control. During that time, a strong background has been built on this experience by the SIAAP and its partners. This common technical culture is one of the key points for its success. Even if the goals of each system were different, even if the culture were specific to each partner, this shared technical background was very helpful to work on the integration of each system not in a single one but to make them interoperable (i.e. the systems are interconnected and can share information and data with one another). This is the other key point: the fact that each one of the parties that were involved in the project kept its real-time control system on his own (see section 1.2.2.5). The project of integrating the different systems is based in connecting them together and not in merging them into one single system.

In other words, when the MAGES project started, the context was mature. This does not mean that it was an easy project, especially regarding the human relationship between partners aspect.

Three things helped to go through these issues:
- The strong commitment of top management of each partner to go ahead in this project;
- The technical challenges aspects of the project made it exciting and every one found an extra motivation for this reason;
- The fact that the project has started with two studies with concrete outputs for all the parties : rainfall data treatment and setup of a real-time data sharing platforms between the SIAAP and each of the partners;
- The financial support from the Water Agency and the Île-de-France Region was also helpful.

The field of experience acquired from adapting this technology is quite broad. It relies on topics as different as:
- The concept of remote control and how to define the organization and rules for the management of the system.
  Beyond this topic there are several questions to address starting from ergonomic features of the man-machine interface to the staff organization. All questions are strongly related to the objectives of the system, its characteristics, :
  - Remote data transmission and transmission networks,
  - Reliability of systems and redundancies,
  - Numerical modeling and data processing,
  - Sensor implementation and maintenance,
  - Maintenance of different kinds of systems,
  - Cyber security.

The output of MAGES's implementation for SIAAP's operators is largely positive. In particular, it allowed:
- to develop advanced skills in hydraulics and urban hydrology in relation to the complexity of certain works and the geographical extent of the SIAAP transport system;
- to develop a new relationship with its partners, to federate the management of the Ile-de-France networks, around shared objectives;
- to take into account the overall operation of the sanitation system managed by SIAAP and the sharing by network operators and water treatment plant of a common tool;
- a particular attention on the WWTPs with a sharing of knowledge of the constraints of the ones and the others. The setting up of the 'weekly operation bulletin' is an illustration;
- a growing interest of the WWTPS for the forecasts given by MAGES on flows arriving to the plants;
- to have a powerful tool to assist in the planning of works shutdown and the updating of the master plan.

Of course there are possible improvements for the tool. Among them, there is one target of the project which has not totally been achieved: the implementation of 'a user club'. This was one of the aims of the 'replay' mode of MAGES and using it in particular as a tool for feedback about experiences. This would move one step more towards the creation of a common culture among the partners in the operation of the sanitation system.

6. Next Steps

6.1 Integrating the recommendation of the updated sanitation master plan

In 2017, an update of SIAAP's sanitation master plan focused on the achievement of the WFD objectives was adopted. This master plan has confirmed the need for implementing storages facilities in order to significantly reduce the pollutant loads discharged in the Seine by the main CSOs and by *Seine-Aval* WWTP.

To achieve these goals three works are recommended in order of priority:
- 100 000 m^3 of storage capacity at La Briche CSO;
- 70 000 m^3 of storage capacity at Clichy CSO;
- 500 000 m^3 of storage capacity at Seine-Aval WWTP.

These works will be implemented based on a step by step assessment of their impacts on the receiving water.

These works and their management rules will be an important evolution for MAGES for an optimal operation of the sanitation system in order to reduce the stormwater impact on the Seine, including their impacts on WWTP performances.

6.2 From a dynamic flow rate management to an integrated pollutants load management and their impact on the environment

Dynamic flow management is one of the ambitious and innovative projects led by SIAAP. Despite the difficulties inherent in this type of project, since 2007 the system has been fully operational and it has become SIAAP's control tower.

As a management tool for a complex system, MAGES is far from having reached its maturity, as the constraints related to effluent pollution and the impact of discharges on the natural environment are not integrated in its current version. It offers significant development prospects and the next steps of the work in progress aims to prepare this development.

One of the important developments in the future is the management of a system that is increasingly complex and more and more responsive with the need for permanent performance because of an increasing pressure on the whole system related to the future population growth and to the forecasted effects of climate change on low flow rates. It means a reinforcement of the constraints reducing in some ways the 'right to make errors'. To make the most of it, increased data collected by a more developed monitoring system will have to be processed in real-time, in order to take into account the changes in the pollutant load and the acceptability of the environment while controlling the cost. Regulatory bodies require to comply with the discharge permits for WWTPs and for combined sewer overflow. The data processing tools are the essential complement to help the operators to make the most of the equipment implemented by the SIAAP. In this sense we are getting closer to 'smart systems', or smart systems capable of adapting to changes in the environment.

This evolution of SIAAP's smart system relies on three complementary fields:
- Making developments to introduce an evolution in MAGES that will make it able to deal with pollutants loads instead of only flow rate;

- Implementing decision support models in the operation of the waste water treatment plants;
- Connecting MAGES to a Seine quality model, to provide a river quality forecast to adjust the waste water treatment performances to the needs of the receiving water in order to meet the environmental quality standards.

6.3 From flow rates management to pollutant loads

Upgrading the system from flow rates to pollutant loads is still a challenge that will require an ambitious change in the system. The objective is to build a numerical model of the pollutant transformation during the sewage transport in the sewer taking into account solid transport and sewage dilution of some pollutants during rain events. The first step will be to collect data to understand the processes that are occurring in the sewer before proceeding to numerical modeling. This will require the development and the implementation of continuous monitoring systems in sewer networks.

6.3.1 Sewage quality monitoring

In several occasions, the system is subject to transitory phenomena at the WWTP inlet. The origin is elsewhere of these, further upstream on the network. In a moderately ambitious context of performances, the incidence of these particular situations was moderate. Today with penalties on performance and ambitious quality goals, things are different.

The variations of the pollutant load at the inlet of the treatment plants is often the origin of the malfunctions. Understanding these variations is often difficult due to the lack of data available. Take the following example: rapid load variations at the inlet of Seine-Aval WWWTP during rainy weather.

With regards to the ups and downs at the inlet of *Seine-Aval* WWTP (see Figure 33), these increase the risk of uncontrolled discharges and therefore of non-conformities to the consent. These are most likely to occur due to the accumulation of solid deposits during dry-weather and their flushing during rainy events. However, without adequate instrumentation, the information required to understand the dynamics of the situation or the respective contributions from each of the 5 sewers to the treatment plant is unavailable. Only a continuous measurement of the turbidity from each sewer would help to understand the situation and to guide any corrective measures. On the basis of this knowledge, provided by the implementation of continuous monitoring more upstream in the networks, it would be possible to consider the development of modeling the deposits and their flushing enabling a pollutant load forecast to be provided.

These metrological developments are an integral part of the MAGES evolution towards a 'MAGES- pollutants flux'. The implementation and deployment of continuous metrology in the sewerage networks is a difficult but indispensable exercise to ensure the operational knowledge of the complex functioning of SIAAP's network. This complexity is related to its extent and diversity of its structure which include: separate and combined sewers, variable pollutant concentrations in time, the type of industrial activities, etc. Therefore this level of detail is a prerequisite to ensure the success of a reliable pollutant loads forecast. The deployment of the instrumentation will be introduced progressively to take advantage of the feedback of experience of Clichy CSO's pilot site which has been equipped with continuous monitoring instruments.

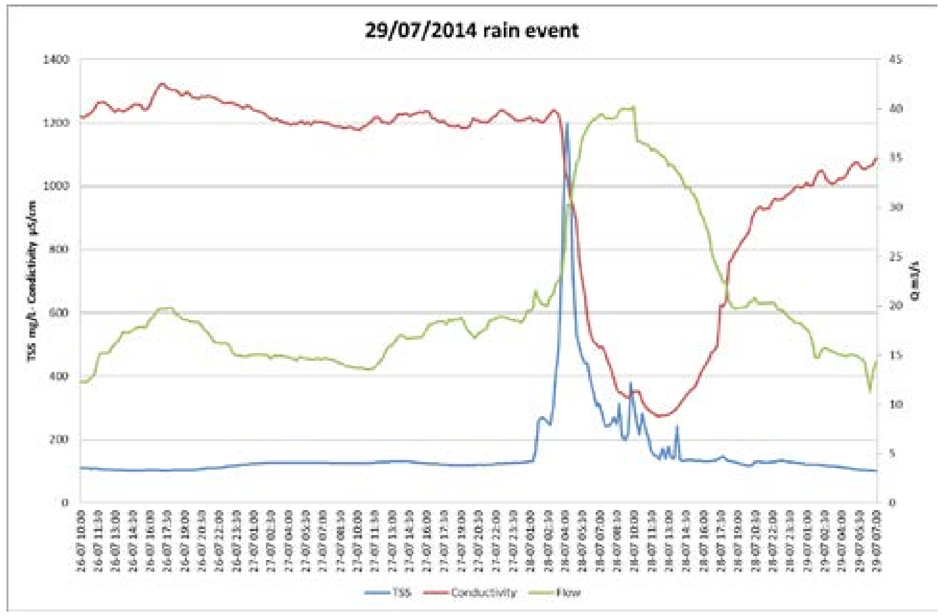

Figure 33. Real-time monitoring at Seine-Aval inlet – Flow (blue), turbidity (green) and conductivity (red)

6.3.2 Treatment plant instrumentation

Another field of instrumentation development concerns the water treatment plants. It is an important link in the system which is of increasing concern to operators. The most recent units now have continuous metrology, which are developed to run more complex plants with reactive processes. Optimised management, in particular for *Seine-Aval* WWTP, requires acquiring all of the knowledge base necessary to build the expertise needed to face all of the operating difficulties. The instrumentation installed in the plant will be an indispensable tool for both piloting this plant, and also for knowledge acquisition. These data will also feed the development of process modeling tools and the construction of precise and efficient control loops.

6.3.3 Metrology in the natural environment

At the other end of the chain is the receiving water, where similar needs exist. In the framework of the PIREN-Seine, a research program on the Seine, SIAAP's R&D department is conducting studies to develop autonomous and continuous measurement systems for the quality of the Seine known as CarboSeine®. These autonomous systems are intended to give an accurate picture of the quality of the Seine which is also subject to continuous variations in quality. Here too, knowledge of these variations is essential to understand the proper functioning of the Seine ecosystem and the dynamics of evolution of the behavior of pollutants released by the SIAAP facilities. In the future, CarboSeine® will also be an indispensable complement to the real-time integrated MAGES system coupling MAGES to a Seine quality numerical model. These data will be used as self-correcting data sets for the model and also validating the good management produced by SIAAP.

In addition, the feedback of these data to MAGES and to the WWTP operators will give a real-time picture of the quality of the Seine and of its possible fragility, thus highlighting the daily context of their performance objectives. These data will also make it possible to report to the State Authorities, or even potentially to users, the real impact of the sanitation system on the environment.

6.4 Developments in modeling

There are three areas in which modeling will continue to develop: 1) the transport of pollutants in the SIAAP networks, 2) the operation of biofiltration treatment plants, and 3) the quality of the Seine. In each case the models to be developed will rely largely on reliable and good quality metrology. As previously mentioned, the situations that must be managed are more and more complex and variable with variations in the distribution of the flows between plants, management of increasingly fine rain weather with the future presence of stormwater basins which will require management to empty. The quality of the Seine is variable too, but to a lesser extent.

6.4.1 Flow modeling

The modeling of the transport of pollutants in the SIAAP networks is an innovative project. Initially the modeling will concern the deposits of suspended matter in the main sewers of *Seine-Aval* WWTP. In addition, due to the continuous measurement of the sewers the behavior of pollutants in certain sectors of the SIAAP network will be measured, even simple modeling such as the dilution of ammonium in rainy weather, may be considered. It will however be interesting, if not necessary to also partner with university research centers to create the modeling.

6.4.2 The modeling of treatment processes

In terms of treatment process, biofilters have the characteristics of being very reactive with response times of an hour or so. This is an asset because they adapt well enough to the rapid variations of flows arriving at the Seine-Aval WWTP. However, it is also a constraint, as any operation error can result in a significant degradation of the discharged water quality. Therefore, the SIAAP is operating an increasingly complex sanitation system while being more responsive, with narrowed margins of error. This situation is particularly true in *Seine-Aval* WWTP, whose regulatory functions or buffer of the western part of SIAAP's system are vital for the proper functioning of the entire sanitation system.

To address this, SIAAP' R&D department is partnering with the University of Laval in Quebec and IRSTEA as part of the Mocopée research program (www.mocopee.com) to model the operation of biofilters. The aim of this program is to build models for predicting the operation of integrated processes in the sewage treatment of SIAAP's plants (i.e. lamellar physicochemical settling works and biofiltration treatment units). Unlike activated sludge treatment, which has been the subject of scientific studies for over 20 years and for which there are good models, there are few modeling tools available for physicochemical settling and biofiltration processes.

These models are constructed to predict the impact of changes in operating conditions (reagent injection, air injection, applied flow rate, applied pollutants loads, etc.) on the quality and performance of the treatment. The use of such tools aids in controlling the processes, both from the point of view of controlling residual concentrations at the outlet, but also from the point of view of controlling energy and reagent costs as well. The models should be seen as an aid for piloting the plant, and not as automated tools. Coupled with a pollutant load forecast and a performance directive, these tools will assist to the operations of these facilities.

6.4.3 Taking into account in real-time the quality of the Seine in MAGES

Another major development of MAGES is its coupling with a Seine quality model. This option was planned from the very beginning of the MAGES project, and implementing this step will be a step forward in management as it is the missing link towards integrated management of a sanitation system. By doing this, the SIAAP would make a very important step forward in sanitation management. This project will make possible to define the downstream sanitation system management constraint in an intelligent and adaptive manner according to the environmental requirements.

Thanks to the PIREN Seine research program, a detailed deterministic model of the Seine quality has been produced: Prose. This model will provide the base of a dedicated model adapted to real-time control.

7. Conclusion

Twenty five years after the implementation of the first SIAAP's real-time control system 'SCORE' and ten years after commissioning the major upgrade of this RTC, one can see how far it has come and several lessons can be learned from this course.

Through this example of SIAAP's real-time control system, it appears that sanitation knows the same evolution as many industrial sectors in the search for security and efficiency: the input of automatization and numerical modeling are more present, making sanitation transition to a mature industry. This appears to be relevant and necessary due to the fact that risks are becoming higher than ever, especially on an environmental point of view: the improvements of the receiving water quality and the public awareness to environmental issues are making failures in waste water treatment unacceptable. In these conditions, failures can now be close to industrial accident. In addition to that, we have to take into account the fact that the regulation is becoming stricter than ever before and in the end the 'right to fail' is no longer acceptable. Another aspect related to the transition through a real industrial approach of sanitation is related to the need of efficiency by searching for the better compromise between cost and performances. Real-time control can help to avoid new investments thanks to an optimized operation of the facilities.

The evolution of the RTC system is the result of a process in which the input of a long experience was one of the major elements for a successful story. This was particularly true if one considers the ambition of the project:

- a large and complex sanitation system combining the different approaches of 5 operators, each SIAAP's department and the SIAAP itself, in the sewage transport which mixes combined and separate sewers;
- the large extent of the territory is also a key issue especially if one takes into consideration the diversity of rain conditions which can vary very much from place to place;
- 5 operators means five cultures and five technical systems to work together, but one of the key points for success was that the project had been driven with the idea that each operator will keep its system and not merge them together in one system.

Ten years after MAGES' commissioning, the following lessons that can be drawn from it are as follows:

- Thanks to the information sharing between all the operators involved in the management of the sanitation system, everyone knows that they are working for a unique system. The recent two floods events of 2016 and 2018 in Paris showed that it is not only a mindset but a reality;
- In a sanitation system which relies on 6 interconnected sewage treatment plants, MAGES played a major role in the necessary shift to a global overview of the operation of the system;

- The organization has evolved to adapt to these new conditions. This has been particularly true for the maintenance works program. Now a three-year coordination program for maintenance work is developed and updated in real-time. This system allows that when shutdown of works are necessary, they are set exceptional discharges of raw water into the receiving waters. A weekly bulletin that gives all the forecast for the next coming week on the conditions for the operation of the system: available treatment capacity of each sewage treatment plant, ongoing works, but also sensitivity of the receiving water to pollution or a general meteorological trend.

The future of the system is the next point of focus for project managers. The new developments are focused on several fields:
- Strengthen the relation between sanitation system operation and their impacts on the receiving water in order to fulfill the achievement of the Water Framework Directive with better operational cost;
- Preparing the transition from a system based on flow management to a system which also takes into account pollutant loads;
- Introducing operation costs as management criteria;
- Preparing for new demands such as swimming in the Rivers Marne and Seine.

These evolutions are required to prepare for the future which will be more constrained due to the increase of population and the effect of climate change on the Seine flows which are forecasted to be lower. As in the past, where engineers and decision makers invested in innovation, one has to prepare for the future with smarter tools for a smarter sanitation system management to fulfill the expectations of the need of a 'water-wise' city.

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