Small Scale System Dynamic Management for Flooding Control

Y. Abou Rjeily*, O. Abbas**, M. Sadek*, I. Shahrour** and F. Hage Chehade***

* Lille 1 University Science and Technology, LGCgE, Villeneuve d’Ascq, France and Lebanese University, Modeling Center, Beirut, Lebanon (Email: yves.abourjeily@hotmail.com; Marwan.Sadek@polytech-lille.fr)
* * Lille 1 University Science and Technology, LGCgE, Villeneuve d’Ascq, France
(Email: oras.abbas@yahoo.fr; isam.shahrour@univ-lille1.fr)
* * * Lebanese University, Modeling Center, Beirut, Lebanon (Email: fchehade@ul.edu.lb).

Abstract

Since decades, cities are expanding due to urbanization process, generating overstressed infrastructures and shortages in resources. This work concerns the stormwater systems within urbanized cities. It evaluates a method to reinforce these utilities against cities expansions. Flooding, system collapse and environmental pollution, as a result of insufficient capabilities, ages and direct release of polluted water, are the major problems encountered while studying the actual state of these systems. Since the major pollution of stromwater arises while water is leaching the impermeable surfaces, flowing through pipes and being mixed with other more polluted runoff, a method consisting of sectoring and decentralizing the remediation of these problems, is proposed. A combination of real time measurements and alternative structures offer the possibility of controlling, directing and pre-treating flows, in order to protect the city and enhance the recharge of water resources at a small system level. Real time monitoring sensors were implemented on Lille 1 University Campus within the SunRise project, in order to test these types of strategies. Quantitative sensors are responsible for indicating the surcharge time of the system, while qualitative sensors are charged to allow the infiltration when measured quality is acceptable. This type of management shows improvements in collecting system capacity, environment protection, treatment plant operation as well as recharging water resources.

Keywords
Monitoring systems; water resources; stormwater systems; alternative structures; case study

INTRODUCTION

The demographic boom, called urbanization, is surcharging cities by overstressing their infrastructures and inducing resources shortages and massive energy consumption (Bello 2014). This is the reason to be oriented toward finding a solution, which could strengthen the constituent of the urbanized cities and recharge their resources. Concerning stormwater systems, studies show that either for combined or separated systems, their failures are presented by flooding and pollution discharges during wet weather (Saget *et al.* 1995; Even *et al.* 2004). In addition, climate change inducing long dry periods followed by severe rainfall events is affecting runoff quality and increasing flooding frequencies (Jung *et al.* 2015; Van der Pol *et al.* 2015). Applications show that alternative techniques based on retention capacity or infiltration potential, present an effective solution for stormwater management (Liao *et al.* 2013; De Paola *et al.* 2015; Monteiro *et al.* 2016). Moreover, in the recent years, studies were focusing on optimizing stormwater networks operations, based on real time monitoring systems during storm events (Mourad *et al.* 2005). In the literature, articles and guidelines for an efficient use of real time monitoring systems are presented (Thomas & Pouet 2006; Rieger & Vanrolleghem 2008). In urban drainage systems, hydrologic-hydraulic simulation models extend the monitoring coverage of the implemented sensors from equipped critical locations, to cover all system components and operations. Thus combining sensors to simulation models, allows to optimize the existing capabilities of the networks, by applying dynamic management taking into account inter- and intra- variability of runoff volume and quality during storm events (Yazdanfar & Sharma 2015). (García *et al.* 2015) presents a review on different types of simulation models and real time control of urban drainage systems.

MATERIAL AND METHODS

This work tends to propose a solution to reinforce stormwater utilities. Since major runoff pollution comes from leaching impervious surfaces, and due to the variability of surface types and human activities within an urbanized city, sectorizing the network in order to manage it, form a good conception for this study. Within SunRise project, which consists in implementing a smart and sustainable city demonstrator on Lille 1 University Campus, a combination between monitoring sensors and alternative structures, was proposed and tested on a small scale system.

Site Description

The chosen sector of Lille 1 University Campus, used in this work, has an area of 30 hectares regrouping different types of surfaces and buildings (restaurant, residences, parking, one to four floors buildings, green areas, etc.). Water evacuation on the campus area is separated in stromwater and wastewater networks. Once exiting the University area, stormwater and wastewater are mixed in a combined system and directed to a treatment plant. This study consider the separated stormwater system and try to propose a dynamic management able to strengthen this utility. The drainage system is composed of pipes having diameters between 150 and 1200 mm. In addition, the network includes lifting pumps, retention tanks, check valves and flow regulators. The studied site presents an average annual rainfall depth around 679 mm with highly intense storm in summer season and an annual temperature range varying between 0 and 23°C. The vulnerability of the stormwater system is presented by floods appearances during the yearly severest storms. Flooding zones are extremely dangerous due to their locations next to university buildings, where underground laboratories exist. Water entering the building threaten the laboratories equipment and working students and researchers. Figure 1 presents the stormwater system and the installed equipment within the studied sector.

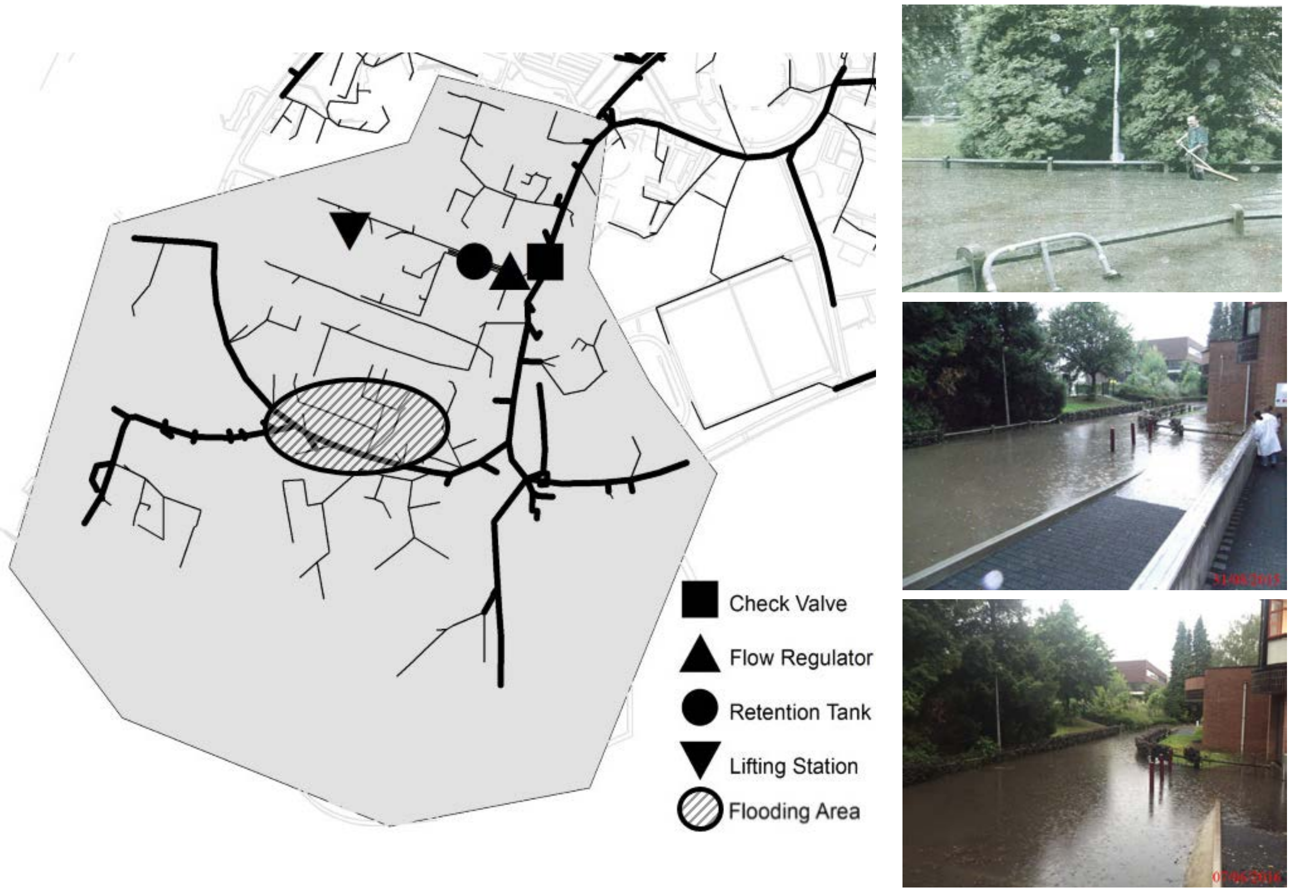

Figure 1: Stormwater System within the Studied Sector with Photos for 3 Different Flooding Events

Real Time Monitoring System

In order to understand the network operation and analyse the flooding occurrences, the infrastructure was equipped with multiple quantitative sensors. Sensors with their locations are presented in Figure 2. A weather station was installed at the centre of the studied sector (Nb 1). Two flow meters were implemented to monitor the system operation. The first was installed at the outfall for measuring the runoff generated from all the studied sector area (Nb 2), and the second placed in the main collector, downstream the retention basin (Nb 3), dedicated to measure runoff, which is generated from a part of the studied sector. In addition, two depth meters were installed in the network. The first was placed in the retention basin to measure the water filling ratio during the rainfall events (Nb 4), while the second was located at the outfall of the studied sector (Nb 5). In order to extend the monitoring zones to cover the entire system operation and response, a hydrologic-hydraulic model was built on EPA-SWMM software. The simulation model was calibrated using Genetic Algorithm and Pattern Search optimization techniques, as described in (Abou Rjeily *et al*. submitted). During the monitoring period, a severe storm event on 31 August 2015 was observed and recorded by the implemented sensors. This event generates flooding appearances in different branches of the system. The network operation subjected to this storm, was quantitatively analysed in (Abou Rjeily et al. 2016), showing the inconvenient of using static equipment, as the check valve and flow regulator presented in Figure 1. A quantitative dynamic management, based on calculating the best valve state schedule, was also proposed and tested in (Abou Rjeily *et al.* 2016). The dynamic management shows the possibility to optimally operate the valve of the retention tank and thus increase its storage capacity. In this work, a qualitative management will be proposed aiming two objectives. The first objective is to support the quantitative management by allocating the tank retention volume to the polluted water. The second objective consists of recharging the groundwater, and thus filling the gap induced by surface waterproofing and urbanization.

Various studies show that most of the pollution of urban wet weather discharges is fixed to suspended solids materiel (Chebbo et al. 1995; Ashley et al. 2005). In the runoff, as in combined effluent during dry weather and wet weather, good correlations between suspended solids concentrations and turbidity measurements were obtained (Deletic & Maksimovic 1998; Fletcher & Deletic 2007). Therefore, a turbidity sensor was implemented inline the network (Nb 6), for measuring the pollution degree of the runoff during the rainfall events.

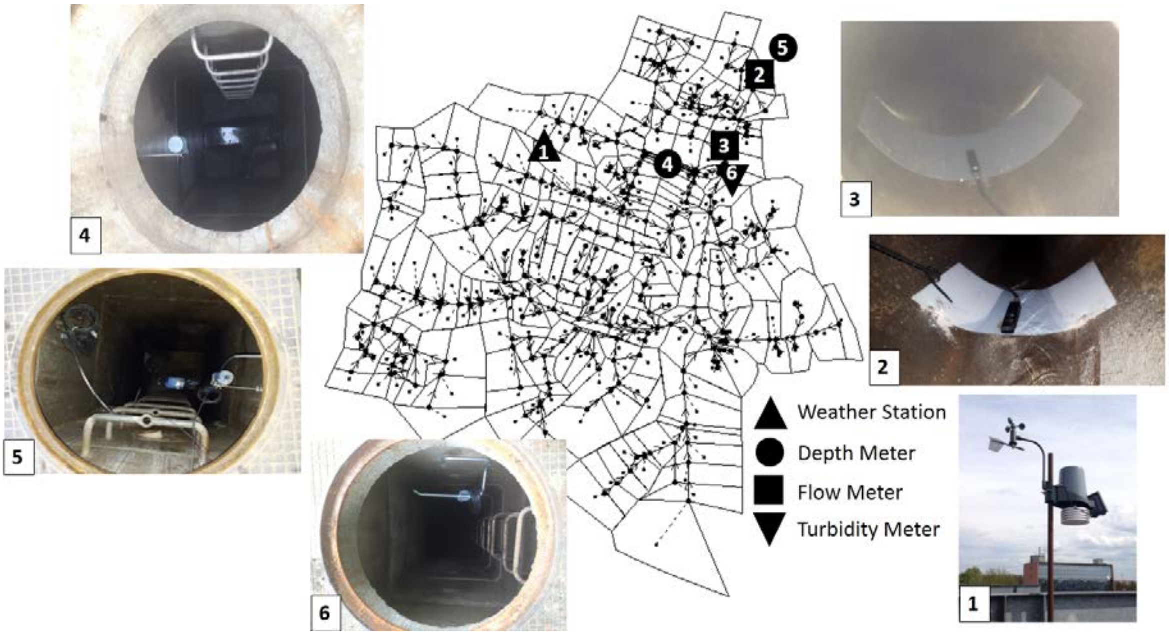

Figure 2: EPA-SWMM Model and Implemented Sensors on the Lille 1 University Campus

Since this work concerns qualitative management and infiltration structures, it should be noted that practicing infiltration techniques in a specified region, should be verified regarding many criteria. Infiltration potential of the supporting soil and groundwater level at the University Campus were checked through geographical maps, provided by Lille municipality. In addition, the area should be verified concerning regulatory constraints and site vulnerability. Infiltration applications could be dangerous, if intake potable water or underground cavities exist in the area. Figure 3 and Figure 4 presents the university campus and its ability for applying infiltration.

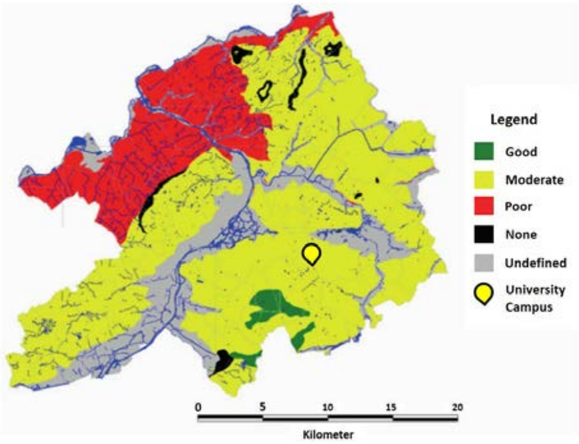

Figure 3: Infiltration Potential Based on Soil Type and the Thickness of Unsaturated Layer

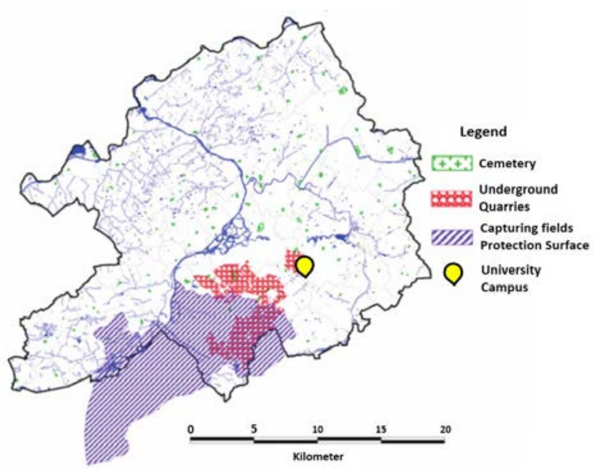

Figure 4: Regulatory Constraints Limiting the Infiltration Applicability

Applying infiltration on the University Campus is favourable since the surface soil is sandy loam and the groundwater level is deeper than 3 m. In addition as presented on Figure 4, no regulatory constraints prevent the infiltration application on the studied site.

Turbidity and Flow Measurements

Once sensors were implemented, collected data was stored in a database, in order to be analysed and evaluated. Characteristics of the rainfall events, where the flow and turbidity were measured by the implemented sensors (Nb 3 and 6 in Figure 2), are presented in Table 1.

Table 1: Characteristics of Rainfall Events

Date	Duration	Total Depth		Peak Intensity	
	(min)	(mm)	(in)	(mm/h)	(in/h)
25/07/2015	320	13.04	0.513	16.76	0.660
30/07/2015	30	5.545	0.218	59.95	2.360
04/08/2015	51	6.651	0.262	86.36	3.400
26/08/2015	46	9.774	0.385	39.62	1.560
31/08/2015	164	24.354	0.959	217.18	8.550
19/11/2015	430	17.287	0.681	22.61	0.890
11/12/2015	172	5.813	0.229	23.37	0.920
30/01/2016	452	11.327	0.446	13.97	0.550

Figure 5 to Figure 12 present the measured turbidity and flows during the 8 different events on the University Campus.

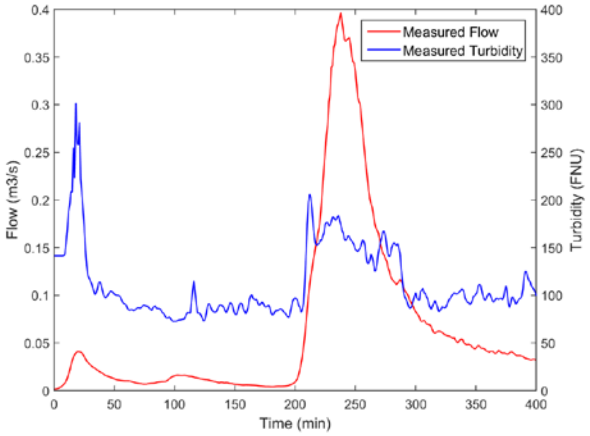

Figure 5: Measured Flow and Turbidity during the Rainfall Event of 25 September 2015

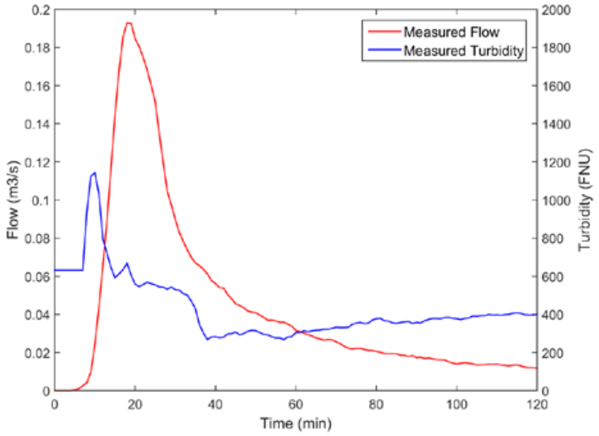

Figure 6: Measured Flow and Turbidity during the Rainfall Event of 30 September 2015

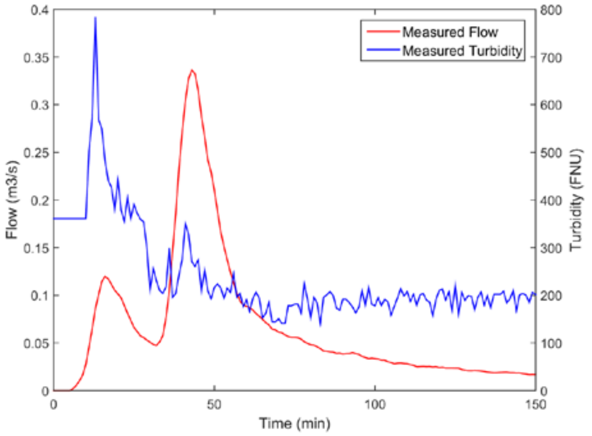

Figure 7: Measured Flow and Turbidity during the Rainfall Event of 4 August 2015

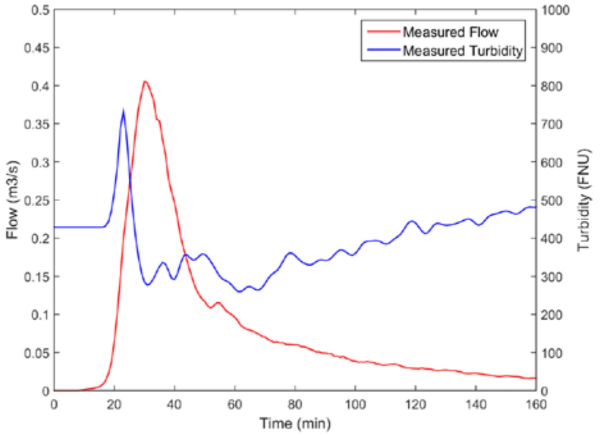

Figure 8: Measured Flow and Turbidity during the Rainfall Event of 26 August 2015

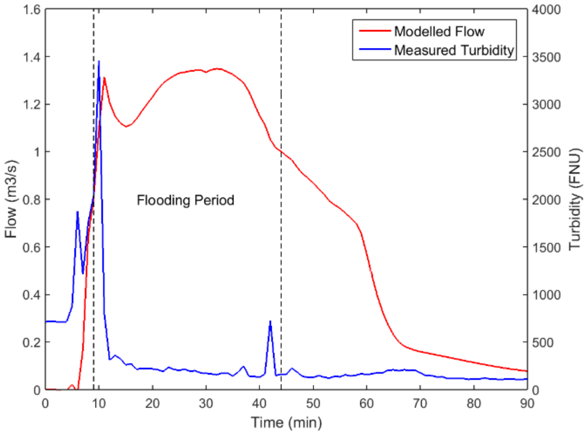

Figure 9: Measured Flow and Turbidity during the Rainfall Event of 31 August 2015

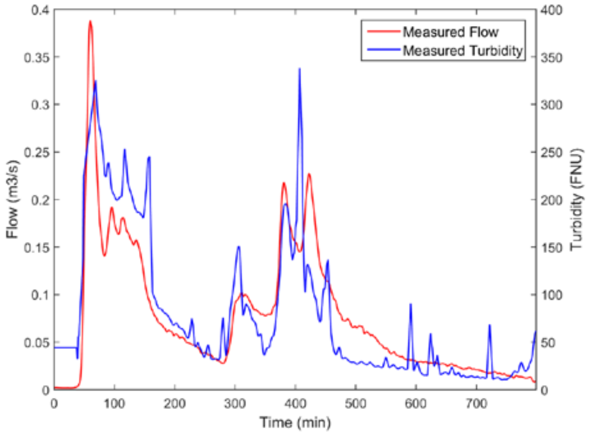

Figure 10: Measured Flow and Turbidity during the Rainfall Event of 19 November 2015

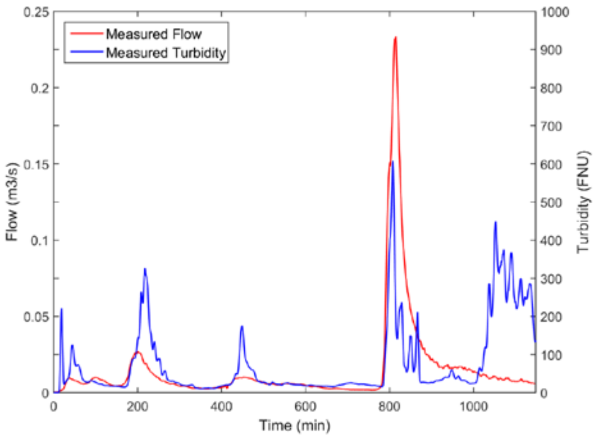

Figure 11: Measured Flow and Turbidity during the Rainfall Event of 11 December 2015

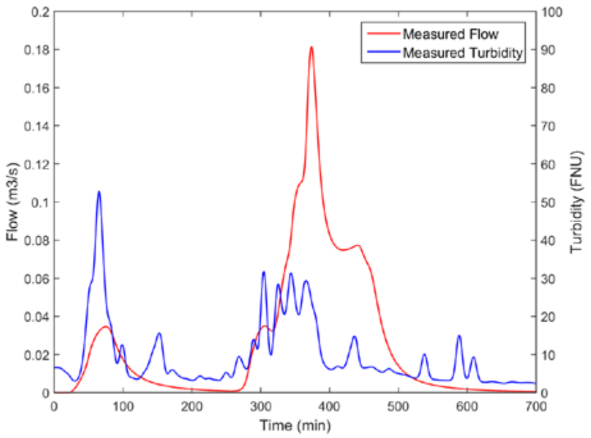

Figure 12: Measured Flow and Turbidity during the Rainfall Event of 30 January 2016

While analysing the received data, presented in the precedent figures, the variability of the pollution degree within the stormwater systems is clearly indicated. Two relationships between turbidity and flow, were noticed. Higher turbidity values come with higher flows, is the first relationship to observe. The second observation indicates that higher turbidity values are more likely to occur with the beginning of the runoff, if sufficient water volume was flowing in the system. These pollutions are majorly produced through leaching the urban surfaces. Since high rainfall intensities have high leaching potential, higher turbidity values are correlated to higher flows, which explains the first observation. In addition, first flows are leaching the biggest layer of depositions occurred during antecedent dry periods, and thus induced higher turbidity values, which explains the second observation.

The variability of pollution degree within the runoff, during the same event, could support the decision of recharging groundwater with clean water, when the runoff represent a low measured pollution. In addition, the obtained results offer the possibility of proposing a dynamic qualitative management that could support and enhance the network capacity, during severe events. The proposed management in (Abou Rjeily *et al.* 2016), was based on calculating the best valve state schedule in reducing the flooding volume. A reduction of 38 m^3 of flooding volumes was found, and thus an increase of 13.6% of the storage capacity of the 280 m^3 retention tank was achieved. In that dynamic management, all the runoff was considered equally polluted and no importance was given for a specified period of floods. In this work, the proposed management is based on qualitative measurements, and by directing clean water to infiltration structures, more storage importance will be given for polluted flows.

Qualitative Dynamic Management

The qualitative management proposed in this study, is based on directing a water volume from a principal manhole to an inspection manhole, where the quality of water is measured. Flow will be directed to infiltration structure, in case of an acceptable pollution was indicated. Otherwise, water will be returned to the stormwater system. The locations of principal and inspection manholes were chosen to be close to the flooding areas and near a green surface, where the infiltration structures could be implemented. Figure 13 presents the locations of manholes participating in the proposed qualitative management.

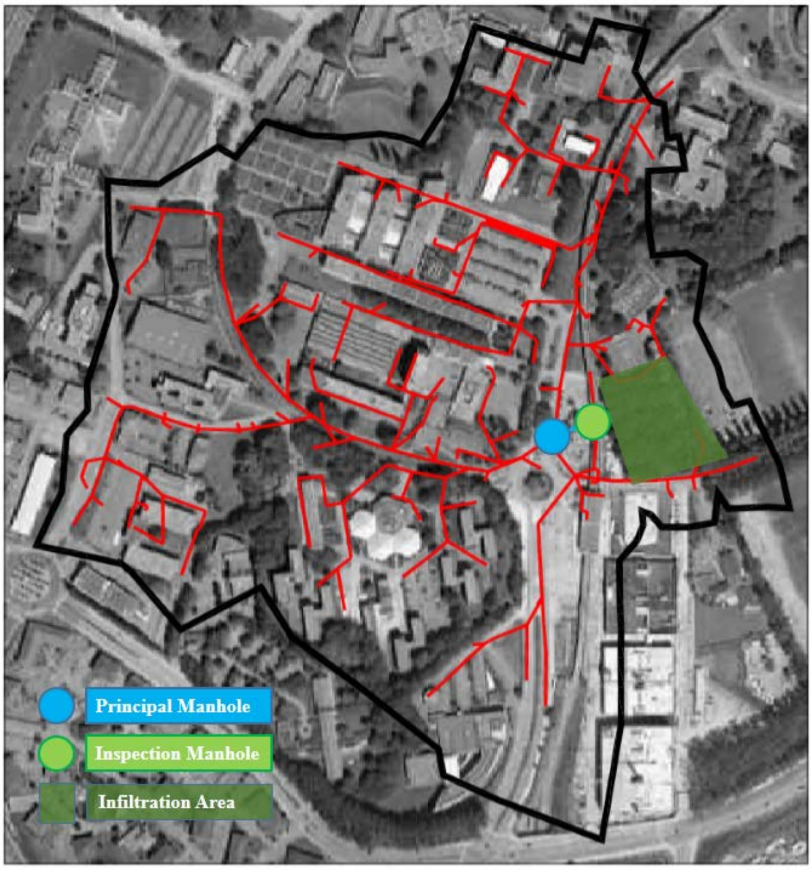

Figure 13: Locations of Manholes for Qualitative Management Application

Since turbidity is related to flow magnitude, the effectiveness of the proposed management in reducing flooding volume, occurring when high flows exist, should be verified. The severe storm event of 31 August 2015, was used to test the efficiency of the proposed management. Few minutes after the beginning of this event, floods appear in different sections of the campus. Turbidity and flow measurements during this event, with the beginning and the end of the floods appearances, are presented in Figure 9. For testing the proposed qualitative management, simulations were conducted on the calibrated EPA-SWMM model, after adding a storage unit, having a volume of 200 m^3 and connected to the principal manhole by a pipe with a diameter of 300 mm. Storage unit was located in the infiltration area, presented in Figure 13. Inflow to the infiltration structure begins after the turbidity measurements were dropped, and stops when water level in the structure is equivalent to 1 m.

RESULTS AND DISCUSSION

For evaluating the potential of such qualitative management, 4 different simulations were conducted. The first simulation consider the operation of the system without the infiltration structure. The second simulation present the system operation after adding to the model the storage unit. The third simulation aims to represent the network operation while adding the storage unit and replacing the static check valve and flow regulator, downstream the retention tank, by a dynamic valve as done in (Abou Rjeily *et al.* 2016). The fourth simulation differentiate from the third one, by adding also a dynamic valve upstream the storage unit, and thus optimally benefit from the storage capacity of the retention tank and the infiltration structure. The dynamic managements of the valves of the retention tank and the added infiltration structure, were both of them based on calculating a valve state schedule composed of 20 values. The calculated vector represent the valve state each 3 minutes time step for a total duration of 1 hour. The state options were limited to open or close valve. The computation of the valve state schedule was done through Genetic Algorithm optimization technique.

The actual operation of the system, represented by the first simulation, indicate a flooding volume and duration equal to 869 m^3 (40.3h), distributed on multiple branches of the network. The second simulation shows a benefit provided by the addition of the infiltration structure in reducing the flooding volume. This benefit was interpreted by the decrease of the flooding volume and duration from 869 m^3 (40.3h) to 789 m^3 (34.6h). The third simulation aims to represent the benefit of implementing an infiltration structure in focusing the storage capacity for the polluted runoff. Since the infiltration occur after turbidity drop, the retention capacity of the tank will be automatically focusing on storing the runoff at the beginning of the event. Compared to the second simulation, this simulation shows a decrease of flooding volume by an amount of 49 m^3 (1.5h), to attain a flooding volume equal to 740 m^3 (33.1h). Thus, an increase of the tank storage capacity by 17.5% is obtained through this simulation. Finally, the fourth simulation had the objective of presenting the potential of dynamically operating the equipment of stormwater system, in enlarging the operation capacity and the retention and infiltration benefits. This simulation illustrates its benefit through a resulted flooding volume equivalent to 729 m^3 (32.6h), indicating an increase in the infiltration structure benefit by 11 m^3 (0.5h), compared to the third simulation.

The obtained results present the benefit of applying dynamic management strategies combined to infiltration techniques, in recharging water resources by clean water runoff and optimally operate the system and its alternative structures. These results could be more important during other storm characteristics. The storm event of 31 August 2015 is characterized by short period of heavy rain, occurring at the beginning of the event. The short intense storms limit the benefits of infiltration structures, since they do not allow the reuse of the storage capacity of the structure, after the infiltration of the already stored water. The efficiency of a dynamic management is also limited compared to a simple open pipe, during such events, since they require to use the storage capacity at the beginning, instead of allocating it to a more critical time. Using Genetic Algorithm, the optimal solutions were found directly after few iterations.

The dynamic management applied for two different valves, consists of calculating 40 different values. For complicated storm events or bigger stormwater networks, algorithms could have difficulties in optimizing 2 VSS with 20 values each. Therefore, another type of management was proposed for the valve of the infiltration structure. The proposed management consists in calculating a constant optimal valve opening ratio, during all the event. After few iterations, the minimum flooding volume, equivalent to 726 m^3 (32.6h), was reached. Comparing the results to the third simulation results, presented earlier, a decrease of flooding volume and duration by an amount of 14 m^3 (0.5h), is found. The resulted optimal constant opening ratio of the valve is equal to “0.9”. In this management, high opening value is more suitable for events that start with high rainfall intensity, while low opening ratio could suit more the events, characterized by late high intensities.

In this section, the turbidity measurements were directly used for indicating the pollution degree of the runoff, and an equation to relate the turbidity to suspended solids or chemical oxygen demand, was not constructed. This proposition was based on considering the stormwater runoff as a clean water when it is characterized by constant low turbidity measurements. Linking turbidity to pollution parameters could help in evaluating the need of a pre-treatment process, before the contact with the environment. In addition, knowing the concentration of the pollution parameters assists in modelling the pollution, and thus running studies and evaluations on unmeasured events. Black box model could also have a great potential in relating flow to turbidity variations.

Stormwater and wastewater evacuated from the campus site, are mixed together in a combined system before being directed to the treatment plant or spilled into the environment as a combined sewer overflow. Since infiltration could not be applied on combined sewer, small scale system management where an ideal solution for Lille 1 University Campus. It is important to note that decentralizing the dynamic management, which is based on infiltration phenomenon, was also very helpful in this case, since not all sites at Lille are favourable to use these techniques or can accept a huge volume of water to be infiltrated as marked in Figure 3 and Figure 4.

CONCLUSIONS

Decentralizing infrastructure management is valuable for problem remediation and system operation optimization, especially in large networks where different types of sectors and human activities are presented. Stormwater presents more benefits while being captured at the upstream branches of the system, before being mixed with more polluted flows. The variability of quality measurements and their range of values, underline the importance of combining real time monitoring with alternative structures for developing a dynamic management. Qualitative management strategy aims to assist the infrastructure operation and recharge water resources. The management proposed in this paper, was based on directing part of clean water to an infiltration structure, in order to recharge groundwater, while storage capacity of the retention tank is more allocated for polluted runoff. Results found in this work, highlight the benefits of such system improvements structures and dynamic managements. In addition, the relationship between measured turbidity and flow allow a weather forecast system to forecast also the variation of a pollution degree and to plan proactively the decisions concerning the flow directions. A hydrologic-hydraulic model allows pollution analysis through qualitative modelling, and could assist in management evaluations and applications, but first an equation linking turbidity to pollution parameters should be constructed. Black box model could also have a great potential in relating flow to turbidity variations.

REFERENCES

Abou Rjeily Y., Sadek M., Shahrour I. and Hage Chehade F. (2016). Dynamic Management through Inline Monitoring of Stormwater Systems. In: *8th International Conference on Sewer Processes and Networks*, IWA, Rotterdam.

Ashley R., Bertrand-Krajewski J. and Hvitved-Jacobsen T. (2005). Sewer solids - 20 years of investigation. *Water Science and Technology* **52**(3), 73-84.

Bello P. (2014). *Stratégie et RSE: Bâtir la stratégie à l'aune des nouvelles responsabilités sociales de l'entreprise*. Dunod.

Chebbo G., Bachoc A., Laplace D. and Le Guennec B. (1995). The transfer of solids in combined sewer networks. *Water Science and Technology* **31**(7), 95-105.

De Paola F., Galdiero E., Giugni M. and Pugliese F. (2015). Sustainable Development of Storm-water Systems in African Cities Considering Climate Change. *Procedia Engineering* **119**, 1181-91.

Deletic A. and Maksimovic C. (1998). Evaluation of Water Quality Factors in Storm Runoff from Paved Areas. *Journal of Environmental Engineering* **124**(9), 869-79.

Even S., Poulin M., Mouchel J.-M., Seidl M. and Servais P. (2004). Modelling oxygen deficits in the Seine River downstream of combined sewer overflows. *Ecological Modelling* **173**(2–3), 177-96.

Fletcher T. and Deletic A. (2007). Statistical evaluation and optimisation of stormwater quality monitoring programmes. *Water Science and Technology* **56**(12), 1-9.

García L., Barreiro-Gomez J., Escobar E., Téllez D., Quijano N. and Ocampo-Martinez C. (2015). Modeling and real-time control of urban drainage systems: A review. *Advances in Water Resources* **85**, 120-32.

Jung M., Kim H., Mallari K. J. B., Pak G. and Yoon J. (2015). Analysis of effects of climate change on runoff in an urban drainage system: a case study from Seoul, Korea. *Water Science and Technology* **71**(5), 653-60.

Liao Z. L., He Y., Huang F., Wang S. and Li H. Z. (2013). Analysis on LID for highly urbanized areas' waterlogging control: demonstrated on the example of Caohejing in Shanghai. *Water Science and Technology* **68**(12), 2559-67.

Monteiro C. M., Calheiros C. S. C., Pimentel-Rodrigues C., Silva-Afonso A. and Castro P. M. L. (2016). Contributions to the design of rainwater harvesting systems in buildings with green roofs in a Mediterranean climate. *Water Science and Technology* **73**(8), 1842-7.

Mourad M., Bertrand-Krajewski J. and Chebbo G. (2005). Sensitivity to experimental data of pollutant site mean concentration in stormwater runoff. *Water Science and Technology* **51**(02), 155-62.

Rieger L. and Vanrolleghem P. (2008). monEAU: a platform for water quality monitoring networks. *Water Science and Technology* **57**(7), 1079-86.

Saget A., Chebbo G. and Desbordes M. (1995). Urban discharges during wet weather: What volumes have to be treated? *Water Science and Technology* **32**(1), 225-32.

Thomas O. and Pouet M.-F. (2006). Sewers (Characterization and Evolution of Sewage). *Wastewater Quality Monitoring and Treatment*, 111-8.

Van der Pol T. D., Van Ierland E. C., Gabbert S., Weikard H. P. and Hendrix E. M. T. (2015). Impacts of rainfall variability and expected rainfall changes on cost-effective adaptation of water systems to climate change. *Journal of Environmental Management* **154**, 40-7.

Yazdanfar Z. and Sharma A. (2015). Urban drainage system planning and design – challenges with climate change and urbanization: a review. *Water Science and Technology* **72**(2), 165-79.

Abou Rjeily, Y., Sadek, M., Shahrour, I., Abbas, O., Hage Chehade, F., El Hachem, E. (Submitted) Auto-Calibration of Urban Drainage Systems Models. *Water Research*