ADAPTIVE STRATEGIES FOR URBAN RAINWATER DRAINAGE SYSTEMS IN CLIMATE CHANGE SCENARIOS

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ABSTRACT

The effect of climate change on the rainwater regime is evidenced in the urban floods generated by runoff, conditioned by changing rainfall intensities, which sewer systems cannot adequately control. This research focuses on the definition of a methodology to determine the feasibility of implementing temporary storage structures (AquaCells structures) in any big city as alternative to reduce peak flow rates, optimizing its location and volume to adapt cities to the conditions of climate change. Using the software Storm Water Management Model (SWMM), the problem was attacked using two approaches: Optimization without Hydraulic Control and with Hydraulic Control. This control was analyzed through three techniques: Model predictive control, Evolutionary games, and Differential games. The results indicate that the urban drainage systems floods could be minimized implementing temporary storage structures and real-time control strategies, even when climate change effects occurs within the established time framework. Additionally, this project tested a methodology to calculate future rain intensities, so cities can be better prepared to face future challenges.

INTRODUCTION

Integrated urban drainage systems were developed as a response to modern issues regarding the management and design of drainage in cities, whose objective was to evacuate rainwater as fast as possible by sending out water outside the city limits. Accordingly, these systems has an important role and must be able to adequately control the runoff water generated in the city (runoff water is a consequence of the interaction between anthropic developments and natural water cycle).

Nowadays, rapid urbanization provokes changes in water consumption patterns as well as soil coverage, and these changes may affect drainage systems. For this reason, these systems are being planned so they can attenuate peak flow rates that are a result from rain events and the factors mentioned.

According to the above, there is a direct correlation between urbanization rate and increments in runoff flows. However, to analyze an increment in those flows that an urban drainage system transports, environmental effects must be considered, since these could alter the water cycle and modify traditional rainwater regimes. This is where climate change takes part in the present study, as it refers to a significant and persistent variation in climate during an extended period of time. Perhaps climate change's most noticeable effect is more extreme climate conditions: droughts will present a minor amount of water, while precipitation events in rainy seasons will be more intense (Camilloni et al., 2016).

Regarding urban floods, there is a convergence between basins' runoff water rise and the impossibility of drainage systems to transport it due to a deficit in its capacity. Most of these systems were designed considering different precipitation events from those that are projected in climate change scenarios. Moreover, floods result in economic losses, public health issues and, in the worst-case scenarios, in the loss of human lives. An example of this was the overflow of the Bogotá River on April 2011, where emergency conditions were declared in more than five boroughs of Bogotá due to the rise in rainwater volumes. This incident affected more than 300,000 people in the city (CIACUA, 2013).

It is evident that an intervention of urban drainage systems is required to mitigate the previously described damages. The alternative to considerate is store water temporally in the system, like some Sustainable Drainage Systems –SUDS propose, which could be a better approximation to solve the problem. Considering the latter, the research project *Urban Drainage and Climate Change: Towards Future Urban Rainwater Drainage Systems* is proposed, where the goal is to analyze the feasibility of implementing temporary storage structures in an existing sewer network. These structures would be smart, using Real-Time Control Systems strategies (RCS), it would also consider climate change effects on precipitation events and peak flow rates to be transported in the network.

The first two phases of this research project were sponsored by Colombia's Administrative Department of Science, Technology and Innovation – COLCIENCIAS the pipe manufacturer PAVCO-MEXICHEM COLOMBIA S.A.S. The technical aspects of the research project are developed by a team from different universities: Universidad de Buenos Aires (Argentina), Universitat Politècnica de Valencia (Spain), Universidade de Coimbra (Portugal), Universitat Politècnica de Catalunya (Spain) and the Universidad de los Andes (Colombia). In terms of its duration, three research phases where stated for the project with different objectives: the first two phases, already finished, consisted in knowledge generation for the relevant research themes and implementing it in a physical model to test out the proposed strategies. The third phase will materialize all the acquired knowledge in a prototype, which will be built in the drainage network of a Colombian city.

CASE STUDIES

Two existing urban drainage networks in Bogotá were selected to carry out the testing process. The selection criteria considered for these networks is presented below.

1. The network's topology must have a branched form.
2. The network must be complex.
3. The sewerage system must be a separated one (i.e. wastewater and rainwater are carried in separate pipes).
4. It must have redundancy between basins.
5. The network must have surcharges.
6. It must have discharge measurement stations near the network

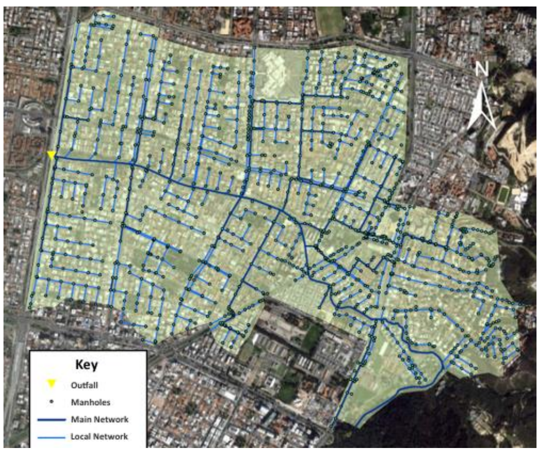


Figure 1. North Chicó sewerage network.

Table 1. North Chicó components summary.

Component	Quantity
Pipes and Sewers	1293
Manholes	1292
Outfalls	1

Figure 2. South Chicó sewerage network.

Table 2. South Chicó components summary.

Component	Quantity
Pipes and Sewers	510
Manholes	509
Outfalls	1

After analyzing several existing urban drainage systems alternatives, located in diverse municipalities and cities in Colombia, two drainage systems in the north of Bogotá were selected, known as North Chicó, South Chicó and Mini-Chicó (a sub-zone in south-eastern South Chicó network), presented in Figure 1, Figure 2 and Figure 3, respectively.

Figure 3. South Mini-Chicó sewerage network.

Table 3. South Mini-Chicó components summary.

Component	Quantity
Pipes and Sewers	83
Manholes	82
Outfalls	1

METHODOLOGY

The research project Urban Drainage and Climate Change: Towards Future Urban Rainwater Drainage Systems is proposed, where the goal is to analyze the feasibility of implementing temporary storage structures in an existing sewer network. The methodology of this research is concentrated in Bogotá, Colombia and follows the steps outlined below.

Assessment of Precipitation Events Considering Climate Change

Its functions were to assess how the new temporary and special distribution of rainfall precipitation events would be when considering this meteorological phenomenon. With that information, it would be possible to generate synthetic rainfall records, which will be the starting point for the other research areas.

To obtain the IDF curves under different climate change scenarios, the results of the daily precipitation from 21 models, called global climatological models (GCMs), for the period between 1986 and 2005. This in order to determine which models reproduced better the climatic conditions in Colombia and then build 24-hour modified IDF curves. (Camilloni et al., 2016).

The modified IDF curves were used through with the instantaneous intensity method to calculate the precipitation hyetograph for a specific event (i.e. storm profile). After this method is applied, a downscaling methodology was applied, to obtain a specific rainfall series for Bogotá so the other research areas can use it.

Modified IDF curves to consider climate change effects were obtained from four different approximations, where the main information inputs were the historic daily rainfall records, IDF curves according to the study area and the results obtained from Global Climate Models – GCMs. There were considered four strategies, listed below.

1. Precipitation events with a high return period.

2. Precipitation intensity projections.
3. IDF curves from GCMs.
4. Delta Change.

Peak Flow Rates Reduction Strategies

This part worked in determining the feasibility of implementing different methodologies to lower peak flow rates in urban drainage systems increasing water storage capacity in the network. Once the existent peak flow reduction techniques were understood, different optimization methodologies were proposed, where the objective was to establish an optimal size and location configuration of these storage structures

Temporary Storage Units

This research project focused exclusively in storage tanks implementation as an alternative to reduce peak flow rates. In terms of new technologies and materials used in storage tanks, this research project focused on AquaCells, that are modular structures designed to perform a proper management of rainwater acting as temporary storage structure or acting as infiltration sumps. Due to its modular shape, it can be easily adapted to different requirements of space conditions and different use scales, ranging from local level to big storage structures (WAVIN, 2003).

Optimal Location and Sizing of Storage Tanks

This project lies in the formulation of a methodology that could lead to an optimal size dimension and location of storage tanks in an existing urban drainage network. The problem was attacked using two different approaches: the first one looks how to stablish the optimal tank's size passively, without considering real-time control, known as Optimization without Hydraulic Control. The second approach considered within its decision variables the diameter of the orifice at the tanks' outlet, being this is the way to consider real-time control strategies in the network, known as Optimization with Hydraulic Control.

Through an innovative component of this research project that consists of providing a connection and integration of a hydraulic simulation software such as Storm Water Management Model - SWMM of the United States Environmental Protection Agency (USEPA), with the optimization software created For this project (Martinez-Solano et al., 2016), this software provides a practical tool to find a set of optimal solutions in a defined network, where the objective function is the minimization of floods or the minimization of the costs of floods

<u>Optimization without Hydraulic Control</u>

The objective function of the optimization problem has been decided to define it in terms of volume since in this way it is possible to consider jointly the investments in retention tanks as well as the excesses of water volumes in the form of floods. This objective function includes three terms (Iglesias et al., 2014):

• Flood level in the different nodes of the network.

• Volume of deposits that must be installed in each of the solutions.

• Maximum volume of water storage in the network. This last option is added to include in the objective function the possibility of including the filling level of the network as part of the objective to be considered.

Optimization with Hydraulic Control

In this optimization approach a decision model was proposed, this model oversaw the determination of optimal volume for each one of the potential storage structures in the system as well as the outlet orifice's diameter for the tanks in the urban drainage system. Because of the pre-evaluation of the study zone it was expected that this network presented potential floods. Later, a set of hydraulic, legislative and operative restrictions were stablished; the feasibility of a solution is conditioned by the simultaneous fulfilment of these restrictions (Cunha et al., 2016).

In this approach, simulated annealing was used as optimization technique taking the analogy from a metallurgical industry application: a raw material is heated, and then when it is getting colder, its physical characteristics are changed (Kirkpatrick et al., 1983, Dowsland, 1993). To provide a connection between the optimizing tool and the hydraulic solver it was used the SWMM Toolkit developed for this project (Martinez-Solano et al., 2016), as it was established previously.

Computational Modeling

This part were focused on the development of models and computational tools that permit to simulate efficiently the proposed methodologies by the other research areas. Due to the innovative character of the proposed method of peak flow rate lowering using real-time control, it was required to have proper computational models to observe the network behavior under the proposed changes. Similarly, it was required to create a program to communicate the optimizing software and the hydraulic simulator; this resulted in the creation of a novel and efficient tool.

EPA-SWMM Toolkit

The Storm Water Management Model (SWMM) is a dynamic simulation engine of flow in sewer systems developed by the United States Environmental Protection Agency – USEPA and will be used in this research project as hydraulic simulator to support work from different research areas. The USEPA provided several tools that allowed the execution of a simulation from an external application as long as network's topology and other network characteristics were previously defined. These tools were extended to get a functions library for the research project named SWMM Toolkit, this library makes the simulation process, results reading and modification of network's characteristics easily (Martinez-Solano et al., 2016).

The development of this toolkit is one of the most important and innovative products obtained during the first two phases of this research project and are presented in Table 1. The toolkit makes the communication process between the hydraulic simulator and the optimization tool in an efficient manner, this is useful to facilitate the solving process of the developed optimization models, being this project a pioneer in the application of this procedures to urban drainage systems problems.

Table 1. Functions included in the Toolkit

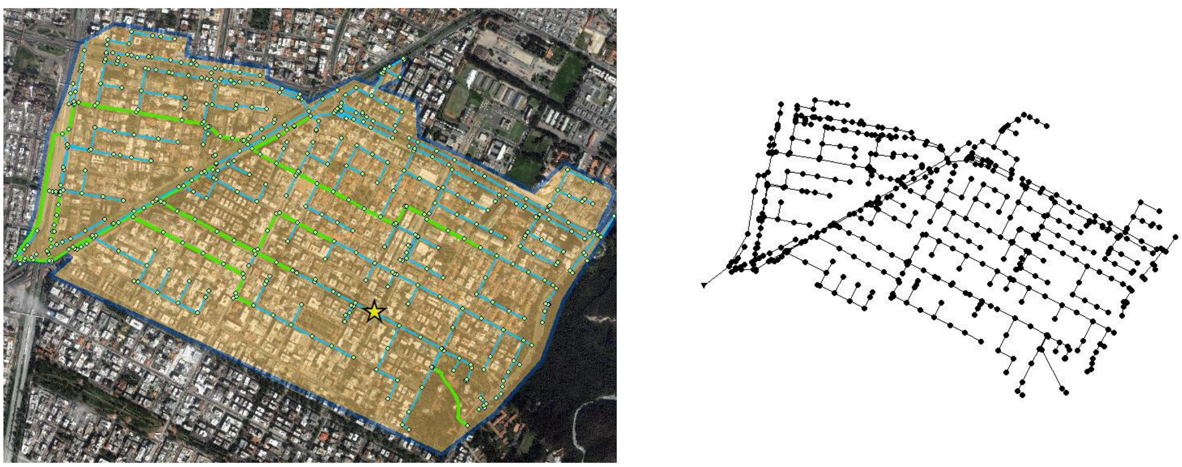
Function Name	Description
Group 1. Project management functions (already available un EPA SWMM)	
swmm_getVersion	Retrieves the version number of SWMM engine
swmm_run	Runs a complete simulation with SWMM
swmm_open	Opens the project for a new execution
swmm_start	Initializes SWMM engine
swmm_step	Executes next time step
swmm_end	Ends the SWMM engine when the simulation has ended
swmm_getMassBalErr	Retrieves the continuity errors when the simulation has ended
swmm_report	Writes results in text format in the report file
swmm_close	Closes the project when the simulation has ended
Group 2. Get functions	
swmm_getCount	Retrieves the number of elements of the specified type
swmm_getNodeIndex	Gets the index of a node from its identifier
swmm_getNodeId	Gets the identifier of a node from its index
swmm_getLinkIndex	Gets the index of a link from its identifier
swmm_getLinkId	Gets the identifier of a link from its index
swmm_getNodeType	Retrieves the type of a node from its index
swmm_getLinkType	Retrieves the type of a link from its index
swmm_getNodeValue	Retrieves the value of a specified parameter of a node from its index
swmm_getLinkValue	Retrieves the value of a specified parameter of a link from its index
swmm_getLinkNodes	-
Group 3. Set functions	
Swmm_setNodeValue	Sets the value of a specified parameter of a node from its index
Swmm_setLinkValue	Sets the value of a specified parameter of a link from its index
Swmm_setLInkGeom	Sets the geometry parameters of a link

Hydraulic Model Generation

To test out the methodologies proposed in the first phase of this project it was necessary to create the hydraulic models in EPA-SWMM, which was the selected simulator for this purpose. The cadastral information of North Chicó and South Chicó, was available as Geographical Information System – GIS offered by Bogotá's water company (Figure 4a). These GIS files contained pipe's characteristics information such as diameters, slopes, starting and ending elevations, and its material; also contained manhole's characteristics such as depth and invert elevation. In these case studies, only pipes compose the local network.

The hydraulic model's generation process will be described below, and the result of this modeling process in EPA-SWMM is presented in Figure 4b.

1. Creation of connections between the main and local pipe networks.
2. Correction of extreme values in ground levels.
3. Ground elevation interpolation.
4. Pipe slopes check.
5. Basins creation.
6. Basins parameters quantification.
7. Topology creation in SWMM input file format (i.e. inp file).
8. Include unevenness between sections.



a) Cadastral information in ArcGIS. **b) Hydraulic model in EPA-SWMM.**

Figure 4. Construction of a hydraulic model in EPA-SWMM from the GIS information available.

Computational Time Reduction

After the hydraulic models in EPA-SWMM were created, it started the test process to evaluate the hydraulic behavior of the model. During the first phase of the project, a first test consisted in increasing the number of network nodes with a lateral flow contribution and registering the variation in the elapsed time to complete the hydraulic simulation. As it was expected, tis test concluded that an increase in the number of contributing nodes represented an increase in computational time. A network with 1360 nodes would take up to 2 minutes to sort out he simulation process, as this is a real-time decision problem, 2 minutes would be unacceptable, so it was required the implementation to reduce the computational time for each simulation.

During the second phase of the project the second test was realized; in this test the computational time was evaluated using the optimization tool specially designed for the project. This test gave similar results to those obtained in the first test, an increase in the number of nodes in the network will result in additional computational time. The problem here relied in the fact that each demand node added to the network resulted in another potential location for a tank to be designed, so if the number of nodes is big enough, the problem would take up to 3 days to get the results (CIACUA, 2016).

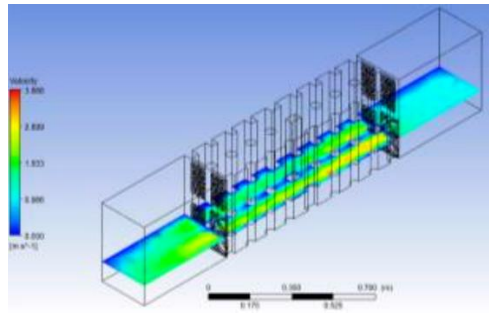
Three actions were defined to reduce computational time and overcome problems in both tests (Iglesias et al., 2014), these actions are described below.

1. New Toolkit: development of a new toolkit that allowed the team to make hydraulic calculations in EPA-SWMM from the toolkit, this means that it was not needed the execution of SWMM's graphic interface.
2. Rainfall-runoff models: the execution of the rainfall-runoff model each time a hydraulic simulation was performed was time consuming and unnecessary, so the solution algorithm was changed and the rainfall-runoff model was executed just once, and for the latter executions the flow rate was replaced for an equivalent contribution in each node in the network.
3. Skeletonization: it consists in network's size reduction in terms of the number of elements in the system, the idea was to provide an equivalent network with less components but without information losses.

AquaCells CFD Characterization

In the second phase of this research project a physical model of AquaCells structures was made to complete the characterization process of this kind of storage structure in urban drainage systems it was developed a Computational Fluid Dynamics – CFD model to get more information about this modular deposit type. CFD allowed to make simulations of different tanks configuration, this was useful to determine important aspects such as energy dissipation in these structures, and provided information to stablish comparative points between AquaCells and conventional storage tanks (CIACUA, 2016).

The Figure 6a presents an experimental prototype built in laboratory for the research project and the Figure 6b presents the CFD models. This consisted of a channel along which several modular blocks are disposed to analyze both, circulating flows and water levels reached at different points of the system. The result is a validated and calibrated model that allows to represent the behavior of this kind of structures in high intensity storms. Thereof, it can be said that these techniques can be used firstly as a tool to characterize larger detention tanks. In addition, such a tool can be used to determine the energy dissipation of these structures in different flow conditions as well as in other configurations to those analysed without the need to spend the enormous amount of money that laboratory experiments imply. Certainly, its use in more depth in the future will allow to analyse larger detention tanks built with this kind of modular structures and the determination of what conditions are like filling and emptying them when heavy rain episodes will occur. (Sanchez-Beltran et al., 2016).



a) AquaCells physical model. **b) AquaCells CFD model.**

Figure 5. Construction of a physical laboratory controlled model and creation of a CFD model for AquaCells structures.

Real –Time Control

This part were focused in the study of real-time control techniques available, which could be applied to real urban drainage systems. The main goal was to find possible modifications on drainage systems, so they could be adapted to respond smartly to situations where there was an important increase in water levels inside the system because of rainwater precipitations which could lead to floods in the city.

Real-Time Control and Urban Drainage Systems

When real-time control systems (RCS) are implemented in urban drainage systems, it is expected that the automated system has the ability to respond properly to situations where drastic variations in precipitation events are presented. Likewise, it can be said that an urban drainage system is real-time controlled if process variables are monitored and used continuously to handle the actuators during its operation (Schütze et al., 2003). RCS algorithms consist in a set of rules that can determine which control action will be taken as a response to the current conditions of the drainage system.

Historically, the main objective of real-time control in urban drainage systems has been the reduction of flood volumes, or the number of floods, without extending the current system infrastructure. Other common control objectives include the prevention of urban floods, the contamination reduction of the water body that receives wastewater and the minimization of operational costs. More recently, other objectives regarding water quality have been considered. Real-time control can manage more than one objective simultaneously if multi-objective control strategies are designed.

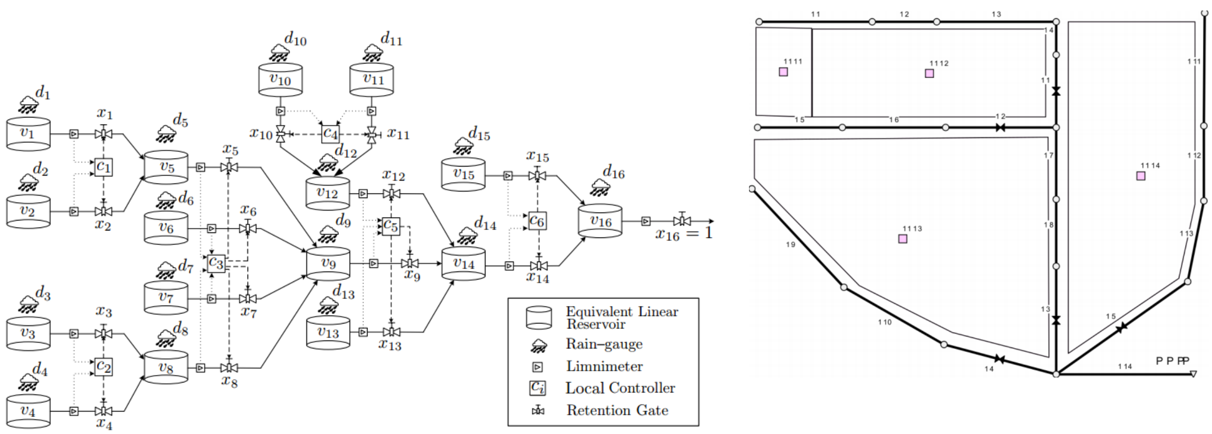
It has been shown that the proper design of real-time control techniques is a reliable, adaptive and cost-efficient solution towards the significant improvement of the urban drainage systems performance (Schütze et al., 2003, Schilling et al., 1996). The main reasons to affirm that real-time control has a positive effect in the urban drainage operation are listed below (Garcia et al., 2015).

1. Most urban drainage systems are planned considering static design rules. However, these systems are operated under dynamic charge/discharge conditions.
2. Climate change makes necessary that drainage systems with a decade's lifespan adapts to new charge conditions. Climate phenomena as global warming just exacerbate this problem.

For this research project, three real-time control techniques have been analyzed to establish the suitability of their implementation in large-scale urban drainage systems. These techniques are:

1. Model predictive control (MPC)
2. Evolutionary games (EG)
3. Differential games (MFG).

In Figures 6a) and 6b), simplified models of the south Chicó network, which are used to validate the algorithms, are shown. Furthermore, MatSWMM (Riaño-Briceño et al., 2016), an open-source toolbox for designing real-time control of urban drainage systems, has been developed to test the control algorithms.



a) Simplified South Chicó model. **b) Model of a branch in the South Chicó network.**

Figure 6. Simplified models used to validate control algorithms. Figure a) is taken from Barreiro-Gomez et al. (2015c), and Figure b) is taken from Ramirez-Jaime et al. (2016).

RESULTS

The mentioned control algorithms have been tested in the south Chicó network, and all of them (MPC, EG, and DG) have shown significant improvements in terms of reduction of flooding volumes and flooding events for critical rain scenarios (Barreiro-Gomez et al., 2015a), (Barreiro-Gomez et al., 2015b), (Barreiro-Gomez et al., 2015c), (Barreiro-Gomez et al., 2015d). The results obtained with the ED-based technique for a typical rain scenario (see runoff hydrograph in Figure 7) in the south Chicó system (see Figure 6a)) are presented in Figure 7. It is shown that the storm water is better distributed throughout the network for the decentralized control case. The upstream reservoirs get more filled and their capacity of use increases to almost the double. The flow downstream is relieved and flooding is avoided. The use of the proposed decentralized controllers and the cascade topology guarantee that the capacities of the reservoirs upstream are more effectively used. The basic hydraulic design is oriented to evacuate the runoff as fast as possible. However, this design approach can lead to flooding events in terminal nodes as seen in Figure 7f). In the case where control is used, reaching the steady state for reservoirs takes more time compared to the uncontrolled case, and this is a consequence of the retaining property provided by the controller. The control objective, i.e., reducing overflows by distributing better the water resource, is satisfied.

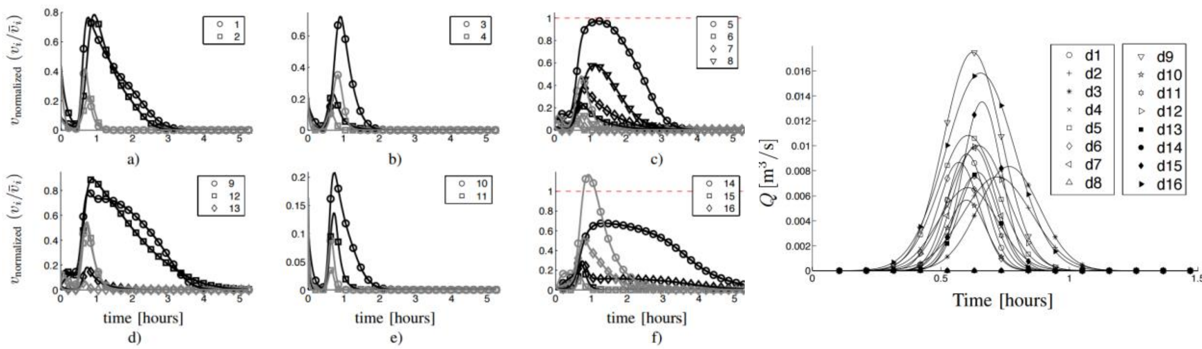
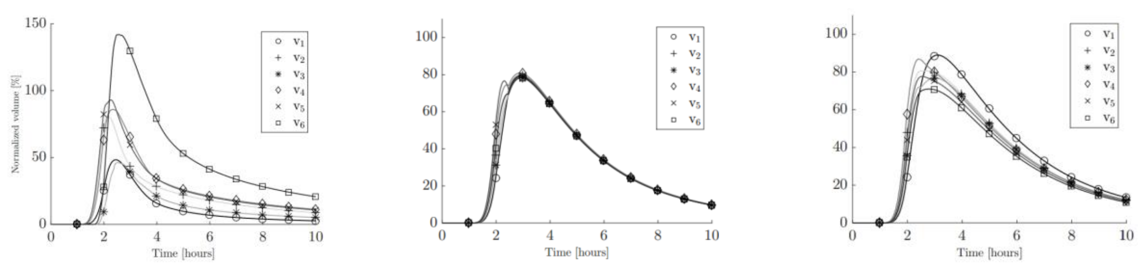


Figure 7. Evolution of the filling ratios in the 16 reservoir modules of the simplified south Chicó system. Gray lines correspond to a scenario without control, and black lines correspond to a scenario with the decentralized controller. Figures a), b), c), d), e), and f) show the reservoirs for the controllers 1, 2, 3, 4, 5 and 6, respectively. Labels refer to the different reservoirs in the UDS. The direct runoff hydrograph of the tested rain scenario is on the right side. This This Figure is taken from (Barreiro-Gomez et al., 2015c).

Additionally, it has been shown that decentralized control techniques not only require less communication infrastructure, but also reductions of flooding events are guaranteed (Barreiro-Gomez et al., 2015c). For instance, in Ramirez-Jaime et al. (2016), this can be evidenced due to results comparing centralized MPC control with DG-based control (see Figure 8). In this work, a consensus-based algorithm is used to equally distribute the runoff among all the reservoirs in one of the branches of the south Chicó system (see Figure8b)). As a result, the controlled system has no flooding.



a) Open-loop response

b) MPC controller on the loop

c) DG-based controller on the loop

Figure 8. Response of the branch system a) without control, b) with MPC control, c) with a DG-based controller. The filling ratio of six branches of the network is controlled. This Figure is taken from Ramirez-Jaime et al. (2016).

CONCLUSIONS

The control algorithms tested in the south Chicó network, and all of them (MPC, EG, and DG) have shown significant improvements in terms of reduction of flooding volumes and flooding events for critical rain scenarios.

The obtained results, after completing the first and second phases of the research project *Urban Drainage and Climate Change: Towards Future Urban Rainwater Drainage Systems*, indicate that the adopted approach for the project has been proper and urban drainage systems floods could be minimized trough the implementation of temporary storage structures and real-time control strategies, even when climate change effects occurs within the established time framework

Secondly, it is important to remark that this paper just intends to present an introduction to the project and give a background to the reader in the development of the research, which will follow its course in the thirds phase of the project. For further details on each project area, we suggest the reader to follow the suggested references throughout this article.

Finally, regarding future work, a third phase of this research is planned; its main goal is to materialize all the acquired knowledge through the first two phases in a real-size prototype in an urban drainage system in Bogotá, Colombia (CIACUA, 2016).

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