

Knowledge base and modelling for urban stormwater management: application to Nice, France

Leslie Salvan

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Leslie Salvan

Connaissances et modélisations pour la gestion du pluvial en zone urbaine : Application à la ville de Nice

Dirigée par *Philippe Gourbesville* et codirigée par Patrice Francour

Soutenue le 18 décembre 2017

Devant le jury composé de : Shie-Yui Liong, Professeur, National University of Singapore Manuel Gómez Valentín, Professeur, Universitat Politècnica de Catalunya Denis Snidaro, Ingénieur, Directeur Technique Régional, SUEZ Luc Allard, Ingénieur, Directeur Général, REGIE EAU D'AZUR Philippe Audra, Professeur, Université Nice-Sophia Antipolis Philippe Gourbesville, Professeur, Université Nice-Sophia Antipolis Patrice Francour, Professeur, Université de Nice Sophia Antipolis













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> by Leslie Salvan

Knowledge base and modelling for urban stormwater management: Application to Nice, France

Directed by *Philippe Gourbesville* and co-directed by Patrice Francour

Defended on December 18th, 2017

In front of the jury composed of: Shie-Yui Liong, Professeur, National University of Singapore Rapporteur Rapporteur Manuel Gómez Valentín, Professeur, Universitat Politècnica de Catalunya Denis Snidaro, Ingénieur, Directeur Technique Régional, SUEZ Luc Allard, Ingénieur, Directeur Général, REGIE EAU D'AZUR Philippe Audra, Professeur, Université Nice-Sophia Antipolis Philippe Gourbesville, Professeur, Université Nice-Sophia Antipolis **Thesis Co-Director** Patrice Francour, Professeur, Université de Nice Sophia Antipolis











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Abstract

This 3-year-PhD thesis has been carried out in the I-CiTy, Polytech' Lab, within a company chair financed by Suez-Environnement. This research has been done in partnership with the local metropolis Métropole Nice Côte d'Azur (MNCA) and the Mediterranean Institute for Risk. Environment and Sustainable Development (IMREDD). Climatic conditions in the Mediterranean region are known to offer rather dry and warm weather conditions. The main obstacle to improve stormwater management in such cities is the traditionally low number of rainy days in a year. However, recent events have shown how surprisingly dangerous and mortal storm events can be. A sadly well-known example is the event that occurred on October 3rd 2015 in the south-east of France. With 21 casualties during a 2-hour-extreme event, local authorities have taken into proper account the stormwater management stakes.

This research work about stormwater management is written while the theoretical background about hydrology, hydraulics and computational tools and methods are widely developed and worldwide used. In the same time however, important issues during flood crisis are not solved and practical solutions take time to be implemented. On top of that, ongoing climatic change will not make things easier and intense events will increase in frequency. To worsen the picture, local economic means in France will not increase to help municipalities and local communities to tackle the issue.

The objective of this thesis is to investigate on the available ways to improve our local knowledge of stormwater related concepts to allow an efficient modelling. The proposed methodology consists in a three-step-approach including:

- 1. A thorough analysis of local topography data;
- 2. The assessment of sewer-surface interactions;
- 3. An integrated approach to model pluvial flood in urban areas.

The results of Step 1 show that topography data is essential in flow path definition and significantly impacts hydraulic modelling results. This leads to Step 2 where it is seen that sewer overflow is one aspect of urban flood issues but represents only part of flood sources. Overland flow generated by runoff should be included in flood models. Then Step 3 presents that integrated urban pluvial modelling is possible with existing tools and can represent the real processes better.

This proposed modelling approach should not be disconnected from the reality of stormwater management practical aspects and current constraints. It is shown how complementary actions can be taken to enrich local knowledge and memory thus allowing a more efficient and wiser modelling process. The needs for collaborative work and wide public education are highlighted. Finally, practical recommendations are given for Nice and similar Mediterranean cities in link with the risk definition of a hazard meeting a vulnerability. Since hazards are not controllable, to control the risk we should focus on controlling the vulnerability, thus improving cities' resilience to pluvial sudden floods.

Keywords: Urban hydrology, Urban pluvial flood, Dual drainage, Mike URBAN, Mike FLOOD

Résumé

Cette thèse a duré trois ans au sein de l'équipe I-CiTy du Polytech'Lab, dans le cadre de la chaire d'entreprise financée par Suez-Environnement. Le travail de recherche a été mené en collaboration avec la Métropole Nice Côte d'Azur (MNCA) et l'Institut Méditerranéen du Risque, de l'Environnement et du Développement Durable (IMREDD). Le climat méditerranéen est connu pour offrir des conditions plutôt sèches et chaudes. Le principal obstacle à l'amélioration de la gestion des eaux pluviales dans ces villes aux conditions favorables est le nombre très peu élevé de jours de pluie par an. Cependant, des événements pluvieux récents ont surpris par leur violence et par la mortalité qui a pu en découler. L'exemple de l'événement du 3 octobre 2015 sur la Côte d'Azur est tristement célèbre. Avec 21 décès pendant un événement extrême ayant duré deux heures, les autorités ont pu prendre la mesure de l'ampleur des risques encourus et des implications de la gestion du pluvial.

Ce travail de recherche sur la gestion du pluvial a été conduit alors que les contours théoriques en hydrologie, en hydraulique et les outils et méthodes de calcul correspondants sont largement développés et utilisés dans le monde. Cependant, en parallèle, des problématiques importantes surviennent pendant les crises sans pouvoir être résolues et des solutions développées peinent à être implémentées en pratique. En plus de cela, le changement climatique en cours ne va pas faciliter les choses et les événements extrêmes devraient voir leur fréquence augmenter. Pour noircir le tableau, les moyens économiques locaux en France ne vont pas augmenter pour aider les communes et autres collectivités à s'attaquer au problème.

L'objectif de cette thèse est de conduire une investigation des moyens à disposition pour améliorer notre connaissance locale des concepts en lien avec le pluvial pour permettre une modélisation efficiente. La méthodologie proposée est composée de trois étapes évolutives incluant :

- 1. Une analyse approfondie des données topographiques locales ;
- 2. L'évaluation des interactions entre les écoulements de surface et le souterrain ;
- 3. Une approche intégrée permettant de modéliser les inondations générées par la pluie en zone urbanisée.

Les résultats de l'étape 1 montrent que la donnée topographique est essentielle pour la définition des chemins d'écoulement et impactent significativement les résultats de modélisation hydrauliques. Ceci conduit à l'étape 2 lors de laquelle on observe que les débordements provenant du réseau souterrain contribuent à l'inondation mais seulement en partie. Les volumes d'inondations générés par le ruissellement de surface devraient être inclus dans les modèles d'inondation. L'étape 3 présente une configuration possible de modèle intégré permettant de mieux représenter les processus réels en jeu.

Cette proposition d'approche du système de modélisation devrait être envisagée en relation avec la réalité des aspects pratiques de la gestion du pluvial et des contraintes actuelles. Il est montré comment des actions complémentaires peuvent être mises en place pour enrichir les connaissances et la mémoire locales, permettant ainsi de mettre en œuvre un processus de

modélisation mieux adapté et plus efficace. Les besoins en travail collaboratif et en éducation du grand public sont soulignés. Finalement, des recommandations pratiques sont données pour Nice et les villes méditerranéennes de même type, en lien avec la définition du risque correspondant au couple danger-vulnérabilité. Puisque l'occurrence d'événements dangereux n'est pas contrôlable et ne peut pas être empêché, le contrôle du risque réside dans le contrôle de la vulnérabilité, ce qui correspond à l'amélioration de la résilience urbaine aux inondations générées par les fortes pluies.

Mots clés : Hydrologie urbaine, Inondations pluviales urbaines, Double-drainage, Mike URBAN, Mike FLOOD

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General introduction

Part A Global context

A.1. Cities and drainage systems

Since human beings have been living in social communities and gathering their belongings and assets in villages, towns or cities, water management has been a struggle. On one side, water supply must be set-up and on the other side, wastewater has to be handled. On top of this "small water cycle" there is stormwater, mostly generated by rain events. Both wastewater and stormwater should be drained out of the city. The main reason why such drainage systems are necessary is public health protection. If either wastewater or stormwater are not drained properly, there is a high risk of diseases propagation through floods. Further reasons belong to the consideration of urban functions which are often interrupted in case of a flood.

As explained by Butler & Davies (2010), urban drainage defines the systems which have been designed to drain wastewater and stormwater out of populated areas. Indeed, drainage is necessary to handle wastewater generated by populations and stormwater generated by rain events. Thus, urban drainage is at the interface between populations and their environment, as presented in Figure 1. It shows already how complex it can be to keep a certain balance between the different processes. The population and the industry consume water and flush wastewater to the system which in the same time might receive stormwater. Part of the wastewater and of the stormwater is treated depending on the system's capacity. The rest of it overflows to the receiving waters. Flooding can be generated at different steps of the process. Urban drainage can be defined through a small water cycle induced by human activities, itself included into the big hydrological cycle which takes place at the scale of the river basins.



Figure 1. Interfaces of the urban drainage system (adapted from Butler & Davies, (2010))

GENERAL INTRODUCTION 15

In the very early history of humanity, human beings had very little impact on their environment as they were living in small groups. Issues rose when those groups became too important to continue in the same way while we started to be willing to control our environment (Butler and Davies 2010). First drains have been built in Iraq (ca. 4000-2500 BC) and first drainage systems were operated in Crete and in the Indus Valley (after ca. 3000 BC) (de Feo et al. 2014). Later the Hellenes and Romans developed sewerage technologies to a greater level (Butler and Davies 2010). Some Chinese dynasties were also involved in this progress. However modern drainage systems reappeared later only in 1850, re-using most of the ancient principles (de Feo et al. 2014). The authors of this review of nearly 6000 years of sewerage history show that sanitation has been greatly developed when civilizations were living under favourable conditions.

Cities worldwide are increasingly concentrating more and more population and economical assets. The world population is expected to increase by 2 billion people by 2050 (Reiter 2012). This observation is made while global climate change has been proved with great changes in worldwide climatic conditions and increasing droughts as well as extreme storm events occurrence (Aerts et al. 2009). With new climatic conditions, new locations at risk will emerge and levels of risks will change in urban areas already at risk (U.N. (United Nations) 2011).

For decades, awareness about urban hydrology challenges have already been stated by several authors, including Niemczynowicz (1999). The predictions made at that time have proven to be true, such as the need for multidisciplinary consideration of urban hydrology in an integrated system. Indeed, the links between urban planning, land use policy, development, regulation, economy, environment and education are very tight. Local community involvement is crucial. The need for accurate and reliable hydrological data was already well understood as a prerequisite to rainfall-runoff modelling improvement. Moreover, the pollution issues towards receiving natural waters were already recognized.

A.2. How do science and practice meet in a demanding institutional context

Nowadays, scientific innovations belong mainly to the modelling tools and methods. While computation facilities have improved, many computational tools have been developed and high-resolution data are increasingly available. Modelling defines any tool which is set-up to represent a part of the reality including selected physical phenomena. Models might be physical to conduct experiments in a lab, or mathematical to run simulation on a computer. It is important to keep in mind that all models of any type are wrong because they are not able to represent all the processes and aspects of the reality. However, they can give useful indications by their results when their limitations and included assumptions are stated together with their simulation's results. In the context of hydrology and hydraulics and their modelling, hydroinformatics has emerged in the late 90's and can be defined as a bridge between water sciences and societal water management (Cunge J and Erlich M 1999). Hydroinformatic applications and tools have been dramatically developed for the last decades and many municipalities are using such tools in their water management.

One challenge lies in the relation between practice and theory: the true understanding of what is behind the model's interface. Very often in hydraulics and hydrology, the model user rarely meets the software developer and involved theory and assumptions might be forgotten while the simulations are running. Sometimes, making the modelling results fit with the reality may become the priority in front of the use of suitable or at least realistic sets of parameters (J. a Cunge 2003; Guinot and Gourbesville 2003).

It is striking to realize that many "innovations" in the domain of stormwater management have been already presented and discussed for several decades. However, on the field, their implementation is not straightforward and in practice the complexity of the issues and local constraints (that are all different between cities) make the policy changes complicated.

This document is written while great institutional changes are ongoing regarding local management in France, including water and river management. Depending on the case, new institutional structures are created or specific water related responsibilities are transferred to different divisions, all the changes occurring in a heavy climate of decreasing budgets. However, we have seen that extreme events are not prone to decrease. There is an urgent need to "do more with less" in the domain of water management, especially in urban areas. One way to achieve this challenge is for example a better understanding of the interconnected issues in the domain of stormwater management and urban drainage in general.

A.3. Context in Mediterranean cities

Climatic conditions in the Mediterranean region are known to offer rather dry and warm weather conditions. The main obstacle to improve stormwater management in such cities is the traditionally low number of rainy days in a year. However, recent events have shown how surprisingly dangerous and mortal storm events can be. A sadly well-known example is the event that occurred on October 3rd 2015 in the south-east of France. With 21 casualties during a 2-hour-extreme event, local authorities have taken into proper account the stormwater management stakes (Prefecture des Alpes-Maritimes 2016; Météo-France 2015a). Five years before, in June 2010, 20 other lives were already lost in an extreme rain event (Artigue et al. 2010).

Casualties and damages caused by flooding are not the only issues related to rainfall. In case of less extreme events, when the population is not at risk, receiving waters are already affected by significant pollution levels.

Nice is characterized by the Mediterranean context with high slopes of low hills shaping a wide variety of urban and suburban catchments draining to the sea. The hydrographic context is specific to the region with great seasonal differences in terms of water quantity. On top of that, the sewer network is complex with some separated and some combined parts.

The main issues are pluvial flooding caused by high runoff quantities and seawater pollution produced by sewer overflow and polluted surface water flow.

A.4. Framework of this thesis

This 3-year-PhD thesis has been carried out in the I-CiTy, Polytech' Lab within an industrial chair financed by Suez-Environnement. This research has been done in partnership with the local metropolis Métropole Nice Côte d'Azur (MNCA) and the Mediterranean Institute for Risk, Environment and Sustainable Development (IMREDD). The expected outcomes of this research work were the development of a local strategy to implement a dynamic management of stormwater in Nice. Eventually, the state-of-the-art and the available knowledge needed to be stated and inventoried before a dynamic or real-time management could be developed. This thesis aims to aggregate the maximum of available information and methodology key element to enable a productive further work in Nice and other Mediterranean cities.

Part B Specific considerations and chosen approach

B.1. Pluvial flash floods

The main received idea about pluvial flash floods in urban areas is that they are due to the surcharged and overflowing drainage network and aggravated by the high proportion of impervious area on the surface. However, the drainage network capacity in terms of pipe size is not always the main issue. Very often the inlet flow does not allow enough volume to enter the pipes (B Russo et al. 2005). Sometimes even the speed of the runoff on the street is too high to enable the absorption of enough flow into the underground network. The first problem might be related to grates size or design but is also related to the situation of clogging of the inlets by surface materials such as tree leaves and waste of different kinds. The second problem described is encountered when the topography of the city features steep slopes. In worst cases, aggravating parameters can be combined.

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Figure 2. Picture of clogged stormwater grates

Worse flash floods generated by highly intense rainfall events are the result of the following processes (which might be combined):

- 1. Almost no infiltration due to the quasi fully impervious surface
- 2. Generation of high runoff volume in a short time, high speed flow in case of steep slope
- 3. Accumulation in low points and flat areas downstream steep slopes
- 4. Clogging of inlets
- 5. Surcharge and overflow of the drainage system

The main difficulty relies in the very fast dynamic of these processes. In contrast with fluvial floods which can evolve in hours or days, urban pluvial flash floods occur in minutes or tens of minutes. If this might be an advantage for the fast drainage of the surface flow after the peak, the question of the warning of the population is crucial as they will be impacted very quickly.

For the rest of the document, flash floods are implicitly defined as due to important volumes of overland flow generated by intense rainfall.

B.2. Problematic and main issues

This thesis is an exploratory applied research work regarding stormwater management and modelling tools and techniques. The investigation started from the open question of real-time control of stormwater sewers in Nice, France. Finally, the large extent of the issues raised by

this very first question made the focus move on towards a wider point of view. Indeed, deeper research was necessary prior to any developments about real-time control.

This thesis aims to picture the current challenges in stormwater management and to describe main obstacles and limitations. More specifically, the problematic is built on the general observation that the research world and the operational field are not always well connected. Therefore, this thesis is developed on a double problematic taking into account both sides.

The main questions are the following:

- How to understand physical rainfall-runoff processes in urban areas better? How to manage stormwater in cities better?
- How to model processes produced by rainfall events in cities for practical applications and management? Which processes should be considered for suitable results in practice?

B.3. Main principles of the methodology

To answer the above-mentioned questions, the methodology encompasses several aspects: an existing model for Nice drainage system and connected surrounding towns is used and other models of smaller extents are set-up in two districts. Three different real cases are used to model what happens at the city-scale, in a 17km²-suburban catchment, and in a 5km²-urban catchment. In parallel with the modelling work, several analyses are conducted following a simple approach to answer the question "what happens when it rains?".

Part C Thesis structure

This thesis is divided into five chapters as presented in Table 1. The current introduction allows to picture the framework of this research work. A thematic review of the state-of-the-art (Chapter 1) together with a wide inventory of local data and knowledge (Chapter 2) cover the necessary elements to build the methodology allowing to study and model physical processes produced by rainfall events in urban areas (Chapter 3). Main observations and results produced are then presented and analyzed (Chapter 4). Finally, practical aspects are highlighted and added to the discussion (Chapter 5) to draw the general conclusions of this thesis.

Chapter	Title	Content
1	Scientific review of the state of the art	Thematic literature review including: meteorological state of Mediterranean regions, urban terrain topography for modelling, Urban hydrology modelling, methodologies to represent urban behavior under rainfall conditions, surface-sewer coupling methods.
2	Data and context in Nice	Local data and information review: rainfall data, rainfall regime analysis, topography and land use data, drainage network data, hydrometric data, existing studies, measurement limitations and improvement proposals.
3	Methodology to model rainfall generated processes in urban areas	Presentation of the global method and explanation of each sub-part, modelling tools, modelling cases, overview of result presentation.
4	Modelling applications and result discussions	Presentation of the results of the different cases and analysis with discussion of the implications.
5	Practical recommendations to city operators and managers	Thematic practical review of stormwater management methods, main aspects to consider to locally improve stormwater management from the existing state with examples.

Table 1. Presentation of thesis chapters and their content

Chapter 1 Scientific review of the state of the art

Part A Introduction

Pluvial flood study in urban areas supposes a wide range of theoretical backgrounds. This topic links many fields such as meteorology, hydrology, hydraulics and hydro-informatic modelling tools knowledge and expertise. Prior to look deeper into most important aspects of this subject, one should examine in detail specificities and background information related to the Mediterranean regions. This part then focuses on the review of urban area specificities and modelling implications. Especially in the Mediterranean region, towns and cities are vulnerable to precipitations and extreme rainfall events. Data regarding rainfall, terrain, network geometry must be considered in an adapted manner in contrast with rural areas. In the same way, software tools that have not always been conceived to deal with urban problematics should be used carefully and parameters should be not only understood but also adapted to urban specificities. Urban areas are characterized by high imperviousness coefficients which generate important runoff volumes in a short time. When adding steep slopes to the situation, very high velocities and discharges are produced. This is an issue that prevents the whole runoff volume from reaching the underground drainage network. Moreover, urban topography and street geometry shape a complex surface network of rather small urban subcatchments with very short response times in the order of several minutes. Consequently, intervention planning cannot be done when the rainfall event starts. Knowledge should be improved to enable a better understanding of the urban rainfall processes, thus giving modellers more insights to adapt urban hydrology and hydraulic models to represent pluvial flood in cities.

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Part B Characteristics of Mediterranean cities in a climate change context

B.1. Main specificities

The Mediterranean Sea is a special part of the globe defined by a closed sea surrounded by reliefs and located on the East-side of a wide Atlantic Ocean and in the North-part of a desert area. Climatic conditions are thus particular as the Mediterranean Basin is a transition area between oceanic, continental and desert climates. Extreme events are frequent, such as high winds, intense rainfall and droughts.

The Mediterranean region of France is characterized by densely urbanized areas squeezed between high hills or mountains and the sea. Urban sprawl is a key issue in the Mediterranean region and urban planning legislation is defined by local authorities (Robert et al. 2015). For example, in the Blue Coast located in the western coast near Marseilles, urbanization pattern has followed the trend of extension of existing built-up areas. The same pattern has been followed in the French Riviera where urban areas are expanding from historical centres, increasing drained areas towards old towns parts. Their vulnerability has thus increased for the last decades.

B.2. Meteorological conditions

Greatest natural risks in the Mediterranean area can be divided between the telluric risks and the risks generated by climatic conditions (GREC-PACA 2016). Mediterranean storm events are known to occur in average three to six times per year, contributing to roughly several months of rainfall in only few hours (Météo-France 2016). These events are generated by unstable humid and warm air masses rising from the Mediterranean Sea confronted to high cold air masses. Two main types of meteorological situations can be observed in the Mediterranean regions: orographic and frontal storm events (Météo-France 2016). In the first situation, hills or mountains have a rising influence on the warm air mass which is cooling as it is rising until the high amount of water vapor condensates producing heavy rainfall. The second situation is characterized by the cold air mass acting as a mountainous chain making the warm air mass rise. Sometimes, the storm cells are able to regenerate by themselves creating a vast cold air surface layer acting again as a relief structure. Very often such storms produce heavy rainfall on a very limited area. Those phenomena are more frequent in fall when the sea is warmer (Figure 3).



Figure 3. Frontal Mediterranean events (reproduced from Météo-France (2016))

It should be stressed that flash floods can be generated by localized intense precipitation which, by definition, can be hardly forecasted. Their spatial structure should be studied to determine better which local catchments will be impacted and will generate strong hydrological responses. For example, a method has been developed using two thresholds and indicator variograms (A. Berne, Delrieu, and Boudevillain 2009). Even though yearly cumulative rainfall shows a global decreasing trend from 1959 to 2009, observations show great disparities between years. At the seasonal time-scale, the decreasing trend concerns mostly the summer and winter seasons (GREC-PACA 2017). This means that extreme autumnal events are prone to fall over very dry soils, thus increasing dramatically potential runoff volumes and important consequences for populations and infrastructures.

The specificities of this region are the great differences which can be encountered in the same territory, such as high hills or mountains, valleys and the vicinity of the sea. In such a context, climatic factors might be impacted by local effects. For example the urban climate of Nice is impacted by topo-climatic mechanisms induced by urbanization, relief and land-sea interface (Carrega 2013).

B.3. Key historical events

Several historical events have become references in terms of exceptional pluvial floods and their documentation is useful to understand better the problematics generated by such

Record of 9 major events

175 mm in 2 hrs

catastrophic events. Most of the time, meteorological context is very specific and accurate predictions are not possible to make. Some of the most intense events in the last thirty years are referenced by Météo-France (2016) and presented in Table 2.

Date	Main location	Characteristics
03/10/1988	Nîmes	420 mm in less than 12 hrs
22/09/1992	Vaison-la-Romaine (Ouvèze)	300 mm in 5 hrs
26/09/1992	Narbonne	292 mm in 2.5 hrs
31/10/1993	Corse	906 mm in 2 days
12/11/1999	Lézignan (Aude)	620 mm in 36 hrs
08/09/2002	Anduze	687 mm in less than 36 hrs
15/06/2010	Lorgues	461 mm in less than 12 hrs

French Riviera

Cannes

Table 2. Most intense events of the last thirty years (Météo-France 2016)

Fall 2014

03/10/2015

(16/09 - 30/11/2014)

Hydrometeorological observations have been gathered for the event on **September 8-9th 2002** which occurred in the Gard Department. During this catastrophic event, 24 casualties were reported and economic damages were estimated at 1.2 billion euros (Delrieu et al. 2005). This event was characterized by a major mesoscale convective system. Sometimes mesoscale convective systems stay over an area, producing enormous amounts of precipitation in few hours.

From the Cevennes to the

Another exceptional event occurred in the Var Department on **June 15th 2010** generating river flash floods at many locations and at least 27 casualties. This event has been reported in detail explaining the probable causes of the disaster (Martin 2010). Meteorological observations have been gathered and thoroughly presented (Artigue et al. 2010) by the observatory KERAUNOS. According to these authors, the main factors explaining the consequences are: the time of occurrence (late afternoon, when many people are commuting, mostly by car), the exceptional violence of the event, urbanization leading to runoff in important proportions.

Recently, another violent event occurred on **October 3rd 2015** over the French Riviera. With exceptional intensities recorded (nearly 200 mm in 2 hours) the damages have been very important and 20 casualties were reported. In Cannes, 174 mm have been recorded in total in two hours (within which 107 mm in one hour) (Figure 4). Such hourly cumulative rainfall has

never been recorded since the records started in 1949 (Météo-France 2015b). Two thorough analyses of this event can be found (in French) (Carrega 2016; Groupe interdisciplinaire de réflexion sur les traversées sud-alpines et l'aménagement du territoire maralpin 2015). An official report from the Prefecture of the Alpes-Maritime Department gives a detailed presentation and analysis of the event as well (Prefecture des Alpes-Maritimes 2016). In this report, the emergency procedures and crisis management aspects are described.



Figure 4. Total rainfall recorded between 18pm and midnight on the 3rd of October 2015 by Antilope Data (Météo-France 2015b)

The characteristics of those events show that the total cumulative rainfall is not the only relevant information and does not inform enough about the severity of the consequences. It is always useful to remember that the risks are generated by the conjunction of the natural hazard with the local vulnerability.

In general, in France, extreme events occur in fall in the foothills of the mountain massifs. Investigations have shown that seven weather regimes can be described, within which four regimes are prone to produce extreme events (Boudevillain et al. 2009).

B.4. Climate change aspects

The Mediterranean region has shown a constant increase of temperature for the last decades, mostly detected for summer temperatures. A yearly increase of around 0.3°C per decade has been detected, for an increase of about 0.4 to 0.6°C for summer temperatures (GREC-PACA 2016). Regarding extreme rainfall event frequency, the conclusion is not straightforward in the Mediterranean Region, since the yearly variability of number of events is very high (Météo-France 2014). Since 1958, the number of days exceeding the thresholds of 190 mm and 15 mm (respectively in dark green and light green in Figure 5) show no specific tendency.



Figure 5. Extreme rainfall events in French Mediterranean Region from 1958 to 2014 (Number of days which total precipitation is higher than 190 mm and than 150 mm, in dark green and in light green, respectively) (Météo-France 2014)

For example, in Nice, average yearly temperature has been increasing since the 1980's (Figure 6). In the same trend, the number of hot days and tropical nights have been increasing (GREC-PACA 2017). Hot days have their maximum temperature higher than 30°C. Tropical nights have their minimum temperature higher than 20°C. Figure 7 shows that the number of tropical nights has dramatically increased in Nice (airport station) from a value of 15 in 1959 to a number of about 60 in 2015. In most pessimistic predictions, this number is expected to rise to 90 in average in coastal cities.

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Figure 6. Average yearly temperature recorded in Nice: deviation to the reference 1961-1990 (Météo-France/ClimatHD, www.meteofrance.fr/climat-passe-et-futur/climathd, in GREC-PACA, 2016)



Figure 7. Number of tropical nights in Nice from 1959 to 2015 (Météo-France, in GREC-PACA, 2017)

The predicted future scenarios regarding precipitations in the PACA-region diverge in their forecast. However, most results predict an overall significant decrease in yearly cumulative values, including the most dramatic decrease in summer. This would produce more difficulties in managing water resources. Moreover, soil surfaces would be drier when the heavy rainfall in fall would occur, generating more severe pluvial flood than nowadays.

This is the reason why studying pluvial urban floods is crucial for the future.

Part C Main input data and considerations for urban hydrology modelling

C.1. Rainfall data for urban hydrology studies

Urban hydrology is a branch of hydrology applied to urban areas. Since the subject can be a city or an urban catchment, the scale of the physical processes is significantly reduced and the anthropic activities have a great influence on them. Wide reviews have been published in the literature (Niemczynowicz 1999; Salvadore, Bronders, and Batelaan 2015). Issues raised by the utilization of rainfall data in the context of urban hydrology have been known for several decades. Engineering and research activities in the urban hydrology field are confronted to considerations such as recording period, rain gauge location, temporal and spatial resolution, synchronization errors between several rain gauges, volumetric accuracy as well as recording gaps (Schilling 1991). All types of rainfall data are not suitable for all urban hydrology (Schilling 1991).

Rainfall data is the first main input required for any rainfall-runoff computation. Rainfall measurements can be done with rain gauges' network and weather radars. Several studies have investigated on the impact of spatial and temporal variability of rainfall events. Two aspects should be considered: the measurement network density and the model spatial discretization. First, rainfall data resolution in space and time should be chosen according to the spatial and temporal extent of the physical phenomena to be observed (Cristiano, ten Veldhius, and van de Giesen 2016). For urban hydrology studies, temporal resolution seems to have a greater impact than spatial resolution with an influence of the input data inversely proportional to the spatial extent of the studied drained area (Ochoa-Rodriguez et al. 2015).

Several studies agree on the benefit to use rainfall radar data for urban hydrology (Alexis Berne et al. 2004; J. Schoorens et al. 2013). However, it should be kept in mind that the rainfall detection of weather radar is an indirect measure since the reflectivity of the rainfall field is measured in fact. This necessary leads to new uncertainties needing quantification (Alexis Berne et al. 2004). Indeed, some studies show that a global approach sometimes gives best results than partially distributed method (Lobligeois et al. 2013). Even though the opportunities are huge, the limits of radar rainfall data linked with the uncertainty of the measure are still to be solved in order to fully meet the input data needs for urban hydrology (A. Berne and Krajewski 2013).

An alternative would be to use a combination technique to take benefit of both methods since rain gauges are recognized for a better accuracy of the measure while a better detection of

spatial variability is obtained with radars. A combination based on error variance minimization would suit well urban hydrology applications (Wang et al. 2013).

C.2. Representation of urban topography

In urban areas, representation of buildings and urban furniture for hydrology purposes raises issues. Several methods have been proposed in the literature (J. Leandro, Schumann, and Pfister 2016; Schubert and Sanders 2012). They all imply a perfect knowledge of the field and accurate datasets. High-resolution photo-interpreted topography data give new possibilities in the domain of urban hydrology modelling as the modeler is allowed to select and include in the digital elevation model (DEM) relevant elements prone to divert flow paths (Morgan Abily et al. 2013; M. Abily, Scarceriaux, and Duluc 2015). The resolution of topography data has a direct impact on hydrological modelling (Horritt and Bates 2001; D. Yu and Lane 2006) as well as the chosen hydrological parameters (Dapeng Yu and Coulthard 2015).

Building representation is one of the key aspects when modelling urban topography and geometry. Buildings are the most important elements in the urban landscape, as well as the main limits of the streets flow in case of a flood. Moreover, roofs surfaces generate part of runoff volume which may be drained directly to the underground stormwater or combined network, or drained to the nearby streets. In the context of green roofs development, roofs surfaces might also be used as pounding surfaces. Different methods have been developed and presented in the literature to represent the impact of buildings on rainfall-runoff processes and on flow diversion. For example, buildings footprint can be elevated, holes can be created to remove the buildings from the computational area, resistance parameter can be increased, or porosity parameter might be modified (Bellos and Tsakiris 2015; J. Leandro, Schumann, and Pfister 2016; Schubert and Sanders 2012). Solid walls methods, also called reflection boundary is the most common method used to represent buildings in urban areas for stormwater studies (Bellos and Tsakiris 2015).

Urban topography is complex due to the high variability of urban furniture. Representative data is not always available. When using high-resolution data, the selection of a reasonable level of detail should be discussed. Based on a global research about sensitivity analysis (Morgan Abily 2015), investigations focused on rainfall in urban areas have been started. When the level of detail in the topography is too high there is a great risk to create urban furniture, which does not exist in the reality or which does not divert the flow (e.g. fences taken as walls). Too much detail is also a challenge for computational tools. For these reasons, data should be thoroughly checked and main urban furniture (i.e. buildings and main walls) may be a suitable level of detail for a 4km²-study area (L. Salvan, Abily, and Gourbesville 2016). This configuration seems also to create a model less dependent on urban furniture evolution.

Regarding the definition of urban catchments, delineation methods for urban areas are necessarily different than the one used for rural areas for river basins and fluvial issues (Jankowfsky, 2011; Parece *et al.*, 2014; supplemented by Parece and Campbell, 2015). The existence of numerous impervious surfaces and surface and underground devices produces great changes in runoff flow direction and dynamic compared to a natural situation (Gironás,

Roesner, and Andrieu 2007). A watershed is defined by a drainage network of meteoric waters with associated contributing drained areas. For more than thirty years, drainage networks have automatically been extracted from digital elevation data (O'Callaghan and Mark 1984). Thibault (1997) defines the three main characteristics of a catchment: its limit, its organization and its composition. Also, five processes produced by the water cycle: evaporation, surface storage, infiltration, surface runoff and sewer flow. Considering urban issues at event scale in adverse conditions with saturated soil, the last two processes are the most important to take into account. Chamoux and Gourbesville (2003) use ArcGIS software tool developed by ESRI to delineate catchments and subcatchments from a digital elevation model (DEM). Rodriguez, Andrieu and Creutin (2003) chose the method of field survey and catchments are delineated from location of stormwater inlets. Lhomme, Bouvier and Perrin (2004) superimpose flow paths obtained from DEM and the stormwater network. In this way, a redefinition of drainage paths is done. Gironás et al. (2010) compare four methods to represent urban topography in a suburban catchment: flow path extraction from DEM, surface digging at streets and pipes location, in a complete or variable way, and the use of two layers, one for the surface, the other one for the underground network. Amaguchi et al. (2012) operate a delineation with vectorbased geometry by dividing the studied area in blocks. Rodriguez, Bocher and Chancibault (2013) compare the use of a DEM, the use of an urban database and the TIN method. Jankowfsky et al. (2013) present a detailed review of different methods used to represent urban topography complexity. A DEM is used for natural areas and vector-based are used to delineate dense urban areas. The superimposition of stormwater networks is also used by Parece and Campbell (2015) by manual correction of DEM, with LiDAR data.

Part D Urban pluvial flooding: concepts and modelling

This section presents main concepts and methods developed so far to represent and model urban response under rainfall conditions.

Urban pluvial flooding is a specific case of flooding which might occur as a single event or in combination with other sources of flooding (*e.g.* fluvial, coastal, or from groundwater). However, the selected case here is the analysis and modelling of processes induced by runoff generated by rainfall only.

D.1. Models for urban hydrology

In the context of urban hydrology, complex interactions occur between natural and artificial processes, such as the exchanges between surface runoff and artificial surface and buried stormwater drainage. The purpose of this paragraph is to recall the main relevant information linked to our problematic of urban pluvial flood and its modelling.

Hydrology modelling requires the understanding of the hydrological physical processes and the local knowledge of the necessary data and information related to hydrological parameters (Musy, Higy, and Reynard 2014; Hingray, Picouet, and Musy 2009). The main input is the rainfall data as the global objective of hydrology modelling is to operate the necessary computations to determine the rainfall-runoff transformations. In other words, the aim is to compute the hydrological response of the study-area in specific rainfall conditions. In urban areas, this means that the main model output is the runoff flow in the city, which might be located on the surface and/or in the underground drainage network.

It has been shown that urbanization has a great but heterogenous impact on the hydrological response of catchments (Salavati et al. 2015a, 2015b).

Two main types of models can describe rainfall-runoff processes (including interception, infiltration, detention storage, evapotranspiration) (O'Loughlin, Wayne, and Chocat 1996): **lumped models** and **distributed models** (Pina et al. 2014). In the lumped case, subcatchments are defined to calculate rainfall-runoff transformation and transport according to their characteristics. A conceptual model is used to represent each subcatchment (Petrucci and Bonhomme 2014). A fair representation of the hydrological response depends on the geometric delineation of the subcatchments and also on the determination of the suitable hydrological parameters. Each subcatchment drains to a unique outlet, which may be a node or another subcatchment. The basic hypothesis consists in setting a uniform rainfall intensity over the whole subcatchment. In distributed cases, finer discretization is made with an element grid. These elements might be regular or irregular. Net rainfall is then estimated for each cell of the grid and corresponding runoff is calculated and transported over the 2-dimensional grid. In this way, surface runoff depends on topography, just like in the reality. Runoff transfer to the

underground network is done only when a stormwater inlet is met along the surface flow path. Thus, in the model, surface runoff should cross the position of a network node to flow into the 1D-network model.

In the study of Pina *et al.* (2014), water levels and flooded areas are smaller in the distributed model than in the lumped model. This can be explained by the fact that some surface volume is retained whereas in the lumped model, the whole volume of each subcatchment is directly drained to each outlet, being a greater pressure for the network at localised flooded nodes. It is shown that distributed models need more complete and accurate data than lumped models. An alternative would be then to mix both approaches by defining lumped subcatchments and distributed areas according to the urban density and characteristics. In this way, the network simplification would not harm the drainage representativeness.

It is possible to draw a first conclusive point saying that a greater accuracy at the spatial scale is not a sufficient condition to get the best results. Input data should comply with this demanding level of accuracy. Thus, high-resolution modelling should not be undertaken without verified and accurate high-resolution data. Moreover, it is recommended in the literature to use a distributed model only when necessary, since too high complexity levels may harm simulation results' quality (Petrucci and Bonhomme 2014). Over-parametrisation represent a risk when the quality of available data is lacking. Too many parameters would then be unknown. Sometimes, in order to calibrate the model, the modeler is forced to define some parameters at a global scale to harmonise the results at the scale of the whole studied domain. These global parameters might have ludicrous values at a small scale inside the model domain. To avoid that, the modeler should collect high-spatial and -temporal resolution data. Hydrological and geographical data should be combined. For example, land use data is essential for urban hydrology modelling. Moreover, the characteristics of the soil and the water table level have significant influence on the catchment response, regardless of the rainfall intensity (Berthier, Andrieu, and Creutin 2004). The study of a Portuguese suburban catchment demonstrates that there are spatiotemporal changes in factors influencing soil properties, thus modifying runoff production patterns with the seasons (Ferreira et al. 2015).

Regarding the computation of hydrology processes in urban areas, it has been shown that diffusive wave approach is not efficient enough and fully dynamic modelling systems should be preferred (Cea, Garrido, and Puertas 2010). The results of a numerical and experimental comparison have shown that computation times are greater for a poorer accuracy for detailed urban flood computations with diffusive wave method.

D.2. Urban flood modelling

In theory, the underground drainage system of a city is designed to drain the street runoff to leave the surface safe for pedestrians and human activities. However, in practice, only a part of the surface runoff can be directly drained to the sewer. This observation explains why very often, urban hydrology studies lead directly to urban flood studies. In case of heavy rainfall, significant amount of runoff volume will remain on the surface causing water accumulation and high velocities depending on the topography. In the meantime, sewer overflow may occur and

interactions are possible at each stormwater inlet. Manholes may be flooded as well and their cover might be removed by the very high surcharge of the underground system. This is the reason why two aspects have been defined in the literature (Wisner and Kassem 1982): (1) the minor drainage system (i.e. the piped drainage system) and (2) the major drainage system (i.e. the streets and surface areas prone to be flooded). Considering both flow in the sewer system and flow on the surface, the concept of "**dual drainage**" has been defined by many authors such as Djordjevic, Prodanovic, & Maksimovic (1999) and Schmitt, Thomas, & Ettrich (2004). The definitions related to this concept as well as a deep historical review are presented by Smith (2006). Even though this concept has been described for several decades, concrete modelling applications have only been possible since computer tools are robust enough for such demanding computations. Recently, a study of a 33km²-area has been done within PCSWMM (CHI 2017) using dual drainage including subcatchments and major and minor elements, showing the need to take into account dual drainage for accurate representation of the city system (Randall et al. 2017).

Urban drainage modelling can be seen under three different approaches, in an evolutive way (Hsu, Chen, and Chang 2002). A first way consists in considering the pipe network only and estimating flooded areas and volumes according to the position of flooded nodes and their spilled volume. In this case, the behaviour of surface flow is unknown. A second approach can be chosen by the modeler. It consists in examining surface flow after underground network overflow. However, this is limited and the most complete approach is the third one, allowing surface flow to access the underground network when capacity is available again. It is thus possible to model the sewer overflow to the surface and the return of the surface flow to the sewer depending on the topography and the network state. Surface-sewer interactions can be modelled.

Several techniques have been developed to represent these surface-sewer interactions. The basic principle is to use a 1D-model of the underground sewer network and a surface model, which may have one or two dimensions. With a 1D-surface model, only the known flow paths are represented, whereas with a 2D-surface model, the surface topography is fully described depending on the resolution. In the second case, the full drainage system including sewer and surface can be modelled. Djordjevic, Prodanovic and Maksimovic (1999) propose a 1D-1D approach. Another couple of study-cases in Dhaka and in Bangkok enables to present the different possibilities provided by the 1D-1D flood modelling approach (Mark et al. 2004). Consistent and cost-effective results are produced. Nevertheless, this method is limited by the often-irregular street geometry and the known surface flow paths, when they overflow, the outside situation is unknown. This drawback might be overcome by a deep analysis of urban topography such as a study of the surface runoff pathways and the pound network, but the success of the approach depends on the quality of digital elevation model (DEM) (Maksimović et al. 2009).

Pina et al. (2014) present a method using a virtual node allowing to model the connection between the 2D-grid or the urban catchment and the 1D-underground-network. In this way, capacity limits in both directions can be described: with an orifice equation in the direction 2D to 1D and with a no-return valve in the other direction.
Other studies propose to adapt the coupling method according to surface land use (e.g. streets, squares, green areas, roofs directly drained to the network...). Surface areas prone to produce surface runoff are thus dealt with at the 2D-model-level, whereas areas directly drained to the network are considered at the 1D-model-level. This means that hydrology modelling is differentiated accordingly to land use defining "1D-areas" and "2D-areas", thus rainfall is applied either in the 1D-network-module or in the 2D-surface-module (Chang, Wang, and Chen 2015). This approach is limited in case of extreme events, when "1D-areas" may produce surface runoff due to very important rainfall intensity.

Jorge Leandro, Chen, Djordjević, & Savić (2009) point out that the main constraint for city operators while handling urban flood is the time constraint. In that way, 2D-surface-models might be difficult to use in real-time. Thus, the authors propose to use the results of a 2Dsurface-model to calibrate a 1D-surface-model coupled with a 1D-sewer-model. This compromise allows to rise the accuracy of the 1D-surface-model without consuming too much computational time. The maximum flood extent is replicated. The authors find that the 1D/1D coupled model often overestimate flood depth at pounds location. They recommend to first setup and calibrate a 1D-2D coupled model prior to set-up a 1D-1D coupled model for emergency applications. An interesting example of a 1D-1D coupled model has been set-up for a studycase nearby Chicago including four modules to model rainfall-runoff transformation, runoff transportation on a 1D-street-network and dual drainage interactions with the underground network (Nanía, Leon, and García 2014). Several scenarios are tested to show the effect of the number of inlets on the drainage capacity of the sewer network and on the flooding. Different criteria are presented to assess the flooding state of the urban area. Another 1D-1D study-case located on the campus of the University of Palermo (Nasello and Tucciarelli 2005) show good prediction of the model but points out the sensitivity of the inlet parameters on the exchange flow thus on the surface flooding results.

Numerous specific software tools and modules have been developed to handle urban drainage issues including surface-sewer interactions. For example: SOBEK (Deltares 2017) developed by Deltares, XP-SWMM 2D (Innovyze 2017b) which is the association of XP-SWMM 1D (Innovyze 2017b) with TUFLOW 2D (BMT WBM 2017) module, ISIS-TUFLOW-PIPE (CH2M 2017) developed by Ch2m, InfoWorks 2D (Innovyze 2017a) developed by Innovyze and MIKE FLOOD (DHI 2014a), the coupling module of the DHI suite. A study shows from the analysis of the modelling results obtained from two different software packages that the choice of the modelling package represent a minor source of uncertainty compared to others (Vanderkimpen, Melger, and Peeters 2009).

Van Dijk *et al.* (2014) review most modelling techniques aiming to represent urban pluvial flooding. This review shows that the tendency is to use 1D-2D modelling systems, with accurate data for 2D-surface flow models. 2D-models alone without coupling may be used to identify vulnerable areas prone to water accumulation. 1D-2D coupling models can prove to be useful for transition areas between hilly and flat districts, obtaining better results. When the most suitable approach is not easily identified, the authors recommend to operate a differentiated method starting with a free-surface-flow model. From this first step, critical locations can be spotted and selected areas can be chosen to perform further analysis between major and minor systems using a 1D-2D coupling method.

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In the category of 1D-2D coupled models, improvements and variations are mostly dedicated to the 2D-surface-model. Different techniques might be used. For example, several level of numerical simplification might be used. Martins, Leandro, Chen, & Djordjević (2017) compare three approaches: a fully dynamic model with a local inertial wave model and a diffusive wave model, all coupled with the same fully dynamic network model. Only little differences are found in the results between the three methods regarding flood extent and depths and volume exchanged. Fully dynamic results can be approached with lower computational cost, in that case featuring low slopes.

Regardless of the modelling method, dual drainage modelling systems are meant to represent both overland flow and sub-surface sewer flow, as well as their interactions. The model ability to represent overland flow is directly linked with its ability to model urban runoff. In other words, the modeller wishes to describe the hydraulic behaviour of streets, which is a necessary step to model the hydrologic response of urban catchments. Prior to the 1D-modelling of dividing flow at street crossing, Nanía, Gómez, & Dolz (2004) have used an experimental model to determine an empirical relationship linking flow distribution to inflow power ratio. The empirical relationship which was determined at one crossing can be generalized for a set of crossings in the 1D-model of an urban area. Another point of view consists in looking at the number and position of stormwater inlets, in the framework of 2D-hydrodynamic models of streets and urban catchments. Several studies have been conducted in Barcelona to examine the surface hydraulic behaviour of streets (B Russo et al. 2005; Russo, Beniamino., Gómez, Manuel., Martinez 2006; M. Gómez, Macchione, and Russo 2006; Manuel Gómez, Macchione, and Russo 2010). For example, B Russo, Gómez, Martínez, & Sánchez (2005) have shown that a specific district was flooded regularly, not because of network surcharge, but because of insufficient stormwater inlets and their poor location.

D.3. Surface-sewer interactions modelling in the context of urban pluvial flood

To model flow interactions between the city surface and the underground sewer, both surface model and sewer model are required. Then, the modeller has to define a mathematical translation of the interactions processes. This means that first of all, actual physical processes should be known and understood. After that, equations should be defined to enable the interactions computation during the modelling process.

Several equations might be used in most modelling packages, such as the orifice equation, the weir equation and the exponential equation. Many studies present their settings of dual drainage models with the weir equation used to represent the free surface flow towards the network, and the orifice equation to model the network overflow through manholes or inlets, sometimes with varying coefficients depending on surface state (Hakiel and Szydłowski 2017). However, it has been shown that simple equations might not always be suitable to represent real physical processes (Bazin et al. 2014). The authors use an experimental facility together

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with a hydrodynamic 1D-2D coupled model including an analytical exchange model to compare experimental and modelling results. The aim is to determine how well the numerical model represents the reality in terms of surface street flow, underground pipe flow and exchange flow. They achieve to simulate global processes using head balance, however disparities occur in case of local perturbations. Another case is presented by Fraga, Cea, & Puertas (2015) with an experimental physical model together with a numerical model of rainfall-runoff processes on a street surface with manholes connected to the drainage system. They find satisfactory results in the comparison especially near the outlet of the system. The transition between free surface and pressure flow shows a well predicted time evolution.

Other types of models can be developed in order to represent physical processes in a comprehensive way, including saturated subsurface flow (Fuchs et al. 2017). In that case, the modelling system also features a particle based transport model and a pluvial flood estimation model. Another point of view is adopted by Chen, Leandro, & Djordjević (2015) by setting up a new model system which considers both inlets and manholes in the interactions processes. The comparison is made with another system which takes into account only manholes. In that way, both the discharge and the surcharge are represented in a more realistic way as water flows first through inlets with smaller dimensions. The search for realism goes far since manholes covers are lifted when the surcharge flow exceeds a threshold. However lacking observations do not allow to conclude on the interest of this new method to represent urban flood consequences better.

Part E Main outcomes of state of the art

In the literature and in nowadays practical studies, the concept of subcatchments is used. This means that the urban terrain is analysed with GIS tools once and manholes are associated to a fixed subcatchment which will directly be drained into the underground pipe network. However, this is a significant simplification of the real processes. Indeed, several reasons have lead the authors to investigate more on this topic: (i) the complex urban topography can produce different flow paths according to the runoff production (e.g. a small wall of 50 cm-height will divert the overland flow as long as the water level does not exceed its height and no longer for above water elevations); (ii) the fact that urban subcatchments can be drained directly into the sewer system is simplistic, in the reality sewer system failures are often linked with reduced inlet capacity due to flow speed or volume and surface clogging can occur.

Most studies present the cause of urban pluvial flooding as being the surcharging and overflowing underground sewer network. However very often in steep slopes or complex urban fabric, pluvial flooding begins when the drainage network is not full yet. Surface problematics need to be examined.

Chapter 2 Data and context in Nice

Part A Introduction

This chapter focuses on data availability and quality. A survey of existing studies and reports related to the topic of stormwater, urban hydrology and urban hydraulics is made.

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This chapter has a double goal:

- 1. it summarizes which data should be searched for in any study or research in the field of stormwater management, which is useful for other cases;
- 2. and it gives an inventory of the available data and documentation related to Nice area stormwater management, which is useful for further research in Nice.

Different types of data exist. In the framework of this research work three main classes are defined: temporal series, spatial data and existing studies or reports. Each of them are important to describe the study-case of Nice.

Part B French institutional context

The reader should be aware of some of the French institutional intricacies. The national territory is divided into regions, which are divided into departments. However, municipalities might be grouped into other types of communities like conurbation or metropolis. Figure 8 shows the location of Nice belonging to the metropolis "Métropole Nice Côte-d'Azur", the department "Alpes Maritimes" and the region "Provence Alpes Côte-d'Azur".



Figure 8. Map of French local authorities

Since 1982 and the beginning of the decentralisation, the responsibilities are shared between the different levels of the French administration, the territorial communities. Municipalities are directed by the mayor and are responsible for primary schools, social housing and building permits for example. Departments are directed by general councils and their responsibilities include social assistance and secondary schools. Regional councils direct regions which are responsible for economic growth, high-schools and land development. The central power of

the French state has global responsibilities such as universities and national roads. France is a (1) deconcentrated and (2) decentralised country. This means that (1) the government delegates powers and duties to persons taking actions in its name in portions of territory; and (2) territorial communities were created as autonomous centres of decision to which the government transfers decision powers, duties and necessary means.

Regarding water management, France is divided into six main hydrographic watersheds (Figure 9) since 1964.



Figure 9. The six French hydrographic watersheds (<u>http://www.lesagencesdeleau.fr</u>)

The six water agencies are public institutions of the Ministry for Sustainable Development. With about 1800 employees, they implement actions to help reducing pollution and protecting water resources. The water agencies implement the objectives of the Water Development and Management Master Plans (SDAGE, French management plans of the Water Framework Directive and their local implementations, the SAGE), by fostering well-balanced, efficient management of water and of the aquatic environment, the drinking water supply, flow regulation and the sustainable development of economic activities.

Water agencies are crucial stakeholders in the implementation of public water policy. They are organised around the principle of the concerted management of river basin districts. Water agencies fulfil their duties within the framework of multi-year action programmes, with the ultimate objective of achieving good water status (Water Framework Directive, October 2000, transposed in 2004 in the French Law).

The priority targets are:

- Reducing pollutant discharges from all sources;
- Guaranteeing the quality of the water supplied;
- Fostering the sustainable development of the economic activities that use water;
- Protecting and rehabilitating aquatic environments and wetlands;
- Regulating flows (natural flood areas and river maintenance);
- Furthering urban-rural solidarity, with respect to wastewater treatment and drinking water;
- Promoting humanitarian solidarity and international cooperation;
- Informing the public and raising the awareness of the public and of schoolchildren about managing and sustainably protecting water and the aquatic environments.

Part C Temporal data

Temporal data are measurements and consists of recorded time series. This category includes rainfall data and hydrometric data.

C.1. Rainfall data

C.1.1. Available data sources

Different sources of rainfall data are available at national and local levels. On top of this consideration, different tools may be used to measure rainfall. A thorough review of available rainfall data should be conducted prior to any study to make sure that the best available data is used.

C.1.2. Local stations

Local rainfall stations have been set-up by the local community, Métropole Nice Côte d'Azur (Figure 11). Oldest stations started their record in 2010. A number of 21 rainfall stations are located in Nice or nearby. Their mechanism is the tipping bucket type. Figure 10 shows an example of typical device used in Nice. A cumulated value of rainfall is recorded every 2 or 4 minutes, depending on the station. The timestep can change along the recorded time series.



Figure 10. Picture of the St-Isidore rain gauge (NCA documentation)



Figure 11. Location of rain gauges operated by the local community Métropole Nice Côte d'Azur (NCA) according to their facility code (© SIG NCA)

C.1.3. Météo-France stations

Météo-France is a French national institute of meteorology. An extended national rain gauge network has been developed by Météo-France since 1958.



Figure 12. National network of rain gauges operated by Météo-France (in red: continuous series between 1958 and 2015)

National data are available from Météo-France with several rain gauges in Nice city area. The main rain gauge is located at the airport. However, in the framework of this research work, the local rain gauge network is selected because of its greater spatial resolution.



Figure 13. Location of rain gauges operated by NCA and Météo-France

C.1.4. Weather radar

Radar devices have been first developed in the World War II context to detect enemy aircrafts. From this experience, it has been decided to develop a weather radar network in 1970 to localise and quantify precipitations. The different types of weather radars are: S band, C band and X band. They may use dual polarization.

Weather radar data are now widely available. However mountainous or hilly areas feature obstacles and are difficult to cover.

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Figure 14. French radar network, situation in summer 2015, 100 km diameter (red: C band, blue and black: S band), 50 km-diameter (green and purple: X band), dpol: dual polarisation © Météo-France (source: http://education.meteofrance.fr/documents/10192/21101/27436-43.png)

For several years, the online application RAINPOL (Novimet 2004) developed by Novimet is available for local authorities of the Alpes Maritimes department. Figure 15 presents processes of the online application of the commercial service.



Figure 15. RAINPOL platform services (extracted from <u>http://www.novimet.com/download/Prospectus_RAINPOL_eng_v3.0.pdf</u>)

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This platform uses polarimetric radar data to produce real-time information and mapping to customers. The "Hydrix + ZPHI" radar system (Moreau, Testud, and Le Bouar 2009; Diss et al. 2009) is used in this context.

C.2. Hydrometric data

Hydrometric data in Nice territory are divided into two main categories such as the probes dedicated to the sewer network self-monitoring and the river monitoring. Network probes can be of radar, doppler or 3-chords-speed type.



Figure 16. Location of the monitoring probes in Nice area

Part D Rainfall regime analysis for Nice area

Prior to use rainfall data an analysis is required. This paragraph focuses on the local rain gauge data belonging to Nice Côte d'Azur metropolis. The idea is to examine successively the temporal and spatial distribution of precipitations at this local scale. The temporal variability of rainfall is analysed according to several time scales. Then spatial variability is added to the picture to get more insights about Nice rainfall regime. Then, local rain gauge data is compared to radar data taken from the HYDRIX data driven by Novimet company (Novimet 2004). The interest is to look at the concordance between these two sources of precipitation data in a local context. Parts of the calculations have been performed using R (R Development Core Team 2017).

D.1. Data analysis

Before using any data, it is important to check the data quality. This has been done, mostly by looking at the gaps and the mistakes in the data. This step prevents the modeller from using unsuitable data. For example, in Nice Metropolis data, year 2016 could not be used as too many gaps have been discovered. Also, several wrong values have been detected and removed, such as negative values or unrealistically high values. They have been considered as no-value-data. To perform the data analysis, a set of seven rainfall stations in Nice is selected, as shown in Figure 17.

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Figure 17. Location of selected rain gauges for temporal analysis of Nice rainfall regime

Then the data of those seven stations has been further analysed regarding two aspects: (1) the temporal variability and (2) the spatial distribution of rainfall. The idea is to simply look at the data under different time-scales and during several events to describe potential patterns.

Finally, a comparison between rain gauge data and weather radar data will be presented. This analysis has been conducted at the event time-scale. All available rainfall stations at the date of the event are selected.

D.2. Temporal variability

The temporal variability is examined at a range of temporal scales: at the year, season, month, day and hour scales. In this way, it will be possible to give useful information for Nice's temporal rainfall characteristics.

However, a great limitation is the length of the available local data which are not older than 2010. For this reason, conclusions from this analysis will only be insights to get a better idea. The same kind of simple study could be done in the future when larger data sets will be available at the same locations.

D.2.1. Annual analysis of temporal distribution

The first step of the temporal analysis of precipitation consists in looking at the yearly scale. The seven rainfall stations data are aggregated in order to get the accumulated rainfall for the whole year at each station. This is done for the years 2010 till 2015.

Figure 18 shows in a first graph the aggregated values of each station by years, then the averaged value of the seven stations is displayed by years.



Figure 18. Accumulated annual precipitation between 2010 and 2015 for a) seven local stations; and b) their averaged value

Even though the data sample is limited with only six years available for local rainfall data, there seems to have a slight increasing tendency between 2011 and 2014. But there is no significant tendency overall.

This is confirmed by the results obtained by other studies with Météo-France data at Nice airport station, as reported in Figure 19.



Figure 19. Yearly cumulative rainfall: ratio to the reference 1961-1990 (GREC-PACA 2016)

Conclusion about annual variability

No specific tendency raises from this graph showing the ratio of yearly cumulative values to the reference. The 11-year-moving average corroborates the conclusion that there is no significant trend in the yearly cumulative precipitation in Nice region for the past years. And there is no significant difference between rainfall stations neither.

D.2.2. Monthly analysis of temporal distribution

When looking at the monthly accumulated values of precipitation, other patterns rise.

Figure 20 shows the monthly averaged values from two points of view:

- From the station side, by making the average over years;



- From the year side, by making the average over stations.

Figure 20. Monthly averaged accumulated precipitation over the twelve months of the year a) between stations for all years, and b) between years for all stations



■ st01 ■ st13 ■ st14 ■ st17 ■ st20 ■ st21 ■ st28



Conclusion about monthly variability

Globally, there is no significant variation between rainfall stations in the monthly pattern over the year. To examine the temporal patterns further, it makes sense to look at the average precipitation between stations at seasonal scale.

D.2.3. Seasonal analysis of temporal distribution

The monthly approach may be simplified by grouping the months in seasons and by looking at the seasonal patterns. In hydrology, seasons are defined by: Spring (March to May), Summer (June to August), Fall (September to November) and Winter (December to February).



Figure 22 shows the temporal distribution of precipitation over seasons.

Figure 22. Seasonal precipitation presented a) by years and b) by mean values over 6 years

Conclusion about seasonal variability

As expected from the local observations, fall shows highest accumulations in general, followed by winter time. No significant variation is observed from the available years, neither between the stations.

D.2.4. Daily analysis of temporal distribution

Another way to look at the precipitation data is to consider the daily scale. The maximum daily accumulated value was taken for each year and each station (Figure 23).



Figure 23. Maximum daily accumulated precipitation for each station and each year

The next question that is raised is whether the daily maximum occurs on the same date within a year for the seven stations. Extracting the date of the maximum daily precipitation has been done. Table 3 presents these extracted dates for each station (in columns) and each year (in lines). Along each year-line, blue colours indicate dates belonging to fall, green to winter and red to spring. Also, same dates and very closed dates are grouped and displayed in the same colour.

Table 3. Extraction of the date of the maximum daily precipitation for each station and each year (blue colours indicate dates belonging to fall, green to winter and red to spring)

Year	Date of maximum for each station/year (dd/mm)									
	st01	st13	st14	st17	st20	st21	st28			
2010		3.	/6	31/10						
2011	6/11	7/1	25/10	10/11	6/11					
2012	26	/10	28/11	26/	/10	27/11				
2013	25/12	18/5	19/12	19/12 20/12 18/5 25/12						
2014	17/1	4/11								
2015	2/	10	3/10			2/10				

In the last six years, six different situations occurred. 2015 is the only case with the same maximum event that occurred in the night between the 3rd and the 4th of October. This observation shows that most of the time, rainfall events are quite localized since several dates were extracted per year.

Conclusion about most intense rainy days

Runoff production is directly linked to precipitations, thus usually, not all the districts are impacted during the same event. However, 2014 and 2015 can be seen as special years since almost only one event appeared to be extracted: the 4/11/2014 and the 3/10/2015. These events are the most intense recent event. This show that critical cases can be observed in Nice, for which heavy rainfall is almost evenly distributed over all the catchments of the city.

D.2.5. Hourly analysis of temporal distribution

The same kind of analysis has been conducted at the hourly time-scale. The maximum hourly precipitation of the seven stations for each year has been extracted. These data are plotted in Figure 24. Then the day and hour of these maximum values were extracted and presented in Table 4.





Figure 24. Maximum hourly precipitation for each station and each year

The maximum hourly precipitation values cover a range from 20 to 100 mm/h approximately. The global trend follows the previously mentioned yearly trend. It can be seen from the graph that over the years, the maximum hourly value is associated to different gauges. There is no geographical pattern in the location of this maximum hourly precipitation. Each part of the city might be impacted.

Regarding the time-distribution of the maximum hourly precipitation, the situation varies over the years. Table 4 presents the most intense hour for each station (in columns) and each year (in lines). Along each year-line, blue colours indicate dates belonging to fall, green to winter and red to spring. Also, same times are grouped and displayed in the same colour.

Year	Date and time of maximum for each station/year (dd/mm hh)									
	st01	st13	st14	st17	st20	st21	st28			
2010	15/11 18h	3/06 16h	25/10 06h	3/06 16h	1 15h					
2011	6/11 04h	6/06 02h	26/09 15h	10/11 02h	6/11 03h					
2012	24/09 12h	12/10 01h		24/09 12h 2			/10 18h			
2013	29/07 07h		14/11 22h	29/07 07h	15/11 02h	29/07 07h	25/12 15h			
2014	7/07 22h	4/11 13h	30/11 23h	7/07 22h		4/11 13h				
2015	3/10 21h	3/10	22h	3/10 21h						

Table 4. Date and time of the maximum hourly precipitation (blue colours indicate dates belonging to fall, green to winter and red to spring)

The same conclusion can be drawn from Table 4 in link with Table 3: gauges share the same most intense hour when an extreme event is observed. This is the case for the 3rd October 2015 event. Other events are highlighted by this analysis: 6/11/2011, 24/09/2012, 29/07/2013, 4/11/2014.

It can be seen from the comparison of both tables that the most intense hour of rainfall does not necessarily occur during the most wet day for several couples of stations / years. This remark demonstrates the specificity of the Mediterranean climate with short and intense rainfall events. However, 2015 proves to feature the most intense event of last years with a strong concordance between daily and hourly maxima.

Conclusions about temporal variability of precipitations in Nice

The regime of precipitations in Nice proves to be mostly variable in terms of seasons with most intense rainfall events occurring in fall. Moreover, the most intense hour of rainfall in a year might not take place during the most wet day of the same year. But it is the case for extreme events like the 3rd October 2015 event.

The consequences are potentially important runoff volumes production in short times, shorter than an hour. Thus, stormwater management in Nice should be developed from this major constraint.

D.3. Spatial distribution of precipitations

The analysis of the spatial distribution of rainfall in Nice city has been performed following the same basic principles as the previous temporal distribution analysis. The interest is to look at the distribution of rainfall quantity over the city at different time-scales. The main question to answer is whether some patterns are followed, which would give insights allowing forecasting of local precipitations.

D.3.1. Annual spatial distribution

To begin the spatial pattern analysis, the rainfall data of the seven rain gauges is aggregated by year over the examined period. The annual cumulative precipitation values are plotted at the location of the rain gauge Figure 25.



Figure 25. Total annual precipitation over years for each rainfall station

No specific trend is observed from the map. To examine the annual potential patterns, it is easier to look at each year separately by calculating a ratio of the total annual precipitation represented by each rain gauge. These maps are presented in Figure 26.

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Figure 26. Ratio of total annual precipitation in each year for each station

The maps of the ratio of each station per year do not allow to give strong conclusions about spatial distribution of rainfall in Nice at the year-scale. However, it can be observed that rain gauges located in the main valleys show more importance than others, especially the three stations located in Var valley.

D.3.2. Seasonal spatial distribution

To examine further potential spatial patterns, we propose to look at the aggregated data of the seven rain gauges per season. The seasons are distributed in the same ways as in the temporal analysis: Spring (March to May), Summer (June to August), Fall (September to November) and Winter (December to February). Figure 27 presents one map per season, with each time a colour-code presenting the mean proportion represented by each station. The seasonal precipitation is averaged over the period 2010-2015.



Figure 27. Mean proportion of seasonal precipitation of each station in each season (red and yellow dots represent values above the average of the total seasonal precipitation)

Each season shows a specific pattern. The summer season seems to differ the most from the three other seasons, with the highest proportion of precipitation falling in the Paillon valley, in the North-East part of Nice. Otherwise, the Var valley is prone to rainfall, as it was seen in the annual analysis. However, it is difficult to highlight a more specific trend. Thus, the next step consists in daily analysis of the spatial distribution of precipitations in Nice.

D.3.3. Daily spatial distribution

In order to deepen the analysis of potential spatial patterns of the precipitations in Nice, the maximum daily precipitation of each station per year has been plotted on a map (Figure 28).



Figure 28. Maximum daily accumulated precipitation from 2010 to 2015 for seven rain gauges in Nice territory

It can be seen from this map that the spatial variability of local precipitation does not follow a particular pattern, given the limited historical data. However, this aspect of the analysis may be continued and enriched by future data.

As a consequence, the hazard of excessive runoff might occur in any part of the city, without any district being more prone to receive extreme rainfall. This shows that stormwater management should be developed in all parts of the city, depending on local vulnerability.

D.3.4. Hourly spatial distribution

Daily spatial distribution does not seem to be fine enough to show any particular pattern. The next step consists in looking at the hourly time scale to check whether some differences between the rainfall stations might be observed.

Figure 29 presents the maximum hourly precipitation of each rain gauge over the years during the period 2010-2015.



Figure 29. Maximum hourly precipitation over years for each station

The map shows disparities between the stations but no particular spatial pattern. We propose to take a wider look at this data by considering the whole available period of time.

Figure 30 presents the average of the previous maximum hourly values for each rain gauge. In this way, instead of examining six years separately, these six years are grouped into an average value which might give more insight about a potential spatial pattern.

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Figure 30. Average of maximum hourly precipitation of each station

This map allows to draw a conclusion about a spatial pattern emerging from the most intense hours of rainfall in Nice. Indeed, it can be noticed that the rain gauges located in the Var Valley (PLNIC 20, 21, 28) seem to be the most exposed to extreme rainfall. In contrast, the lower part of the Magnan valley (PLNIC 13) looks less exposed. This can be linked with the specificity of the Magnan valley which is significantly narrow, while the widely open lower Var valley is more prone to receive perturbations coming from the West and from the sea.

D.3.5. Event-scale spatial distribution

Rainfall data is recorded at a 2-minute-timestep which offers the possibility to look at a finer scale. In this way, the event dynamic might be observed. The main question is whether a specific pattern might exist during rainfall events. Are there areas where more precipitation is recorded according to event types, or seasons? This paragraph explores this issue.

The event selection has been done focusing on the first two maxima of daily cumulated precipitation of each available year in local data. The events lacking data are not taken into account. Eventually, 11 events are selected between 2010 and 2015. These events are divided in two groups of six most intense fall events, and five other less intense events, among which three events occurred in summer.

Figure 31 presents the maps of the group of six, while Figure 32 presents those of the group of five. For each event map, the average between all stations was calculated (Table 5) and the stations are coloured in green when their contribution is below the average, in red when they contribute to a quantity above the average.



Figure 31. Ratio to the average for the first six most intense events



Figure 32. Ratio to the average for the next five most intense events

Event number	Date	Duration (hh:mm)	Average total precipitation between 7 stations (mm)
1	03/10/2015	2:11	79.7
2	26/10/2012	2:32	43.5
3	04/11/2014	2:39	40.4
4	13/09/2015	0:59	33.4
5	10/11/2014	1:23	32.8
6	24/09/2012	0:39	28.3
7	08/09/2010	0:48	19.8
8	29/07/2013	0:45	19.4
9	30/09/2012	0:40	19.2
10	14/06/2015	0:48	19
11	25/08/2012	0:41	14.6

Table 5. List of selected intense events for spatial distribution analysis

The contribution of each station has been examined for each event independently. A specific pattern does not emerge clearly from these maps even though there is a clear greater contribution from the rain gauges located in the valleys.

We propose now to look at these eleven events together and to compare how many times each rain gauge has been below and above the event's average. The results of this approach are presented in Table 6. The location of the rain gauges is recalled in Figure 33 with their situation in the topography.

Event Station	1	2	3	4	5	6	7	8	9	10	11	% over 11 events
PLNIC1	59.00	45.80	0.2	43.20	26.60	31.00	18.00	22.60	6.40	20.40	26.80	55%
PLNIC13	72.6	43.2	36.2	36.8	28.6	11.8	17.6	28.2	25.6	25.6	4.4	36%
PLNIC14	118.2	15	60.6	6.8	22.8	27.4	0.4	9.2	2.4	16	10.8	18%
PLNIC17	72	53.4	15.8	33	29.4	42.6	25	16.2	40	23.4	20.2	55%
PLNIC20	110.2	56.8	42.8	39.2	60.4	41.2	37.80	8.4	41	34.6	9.6	82%
PLNIC21	71.8	48	65.8	41.8	41.8	25.6	29.4	24.8	11.4	9.4	12	55%
PLNIC28	54.4	42	61.2	33	20	18.4	10.2	26.4	7.4	3.6	18.2	27%

Table 6. Visualisation of rain gauges which accumulated precipitation is above the event average (values above the event's average are in blue)



Figure 33. Location of the highlighted rain gauges in link with the topography

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From these results, a tendency seems to appear. The explanation of these results might come from the topography of Nice area. As main valleys consist in the Var and the Paillon valleys, most precipitation falls within these valleys and at a close distance from the sea. It should be noticed that PLNIC 13 is located within another valley which is narrower than the other two. This could explain that less rainfall quantity reaches this point. Of course, these results should be improved with a higher number of rainfall stations and longer recorded time series. But these pieces of information are already useful insights.

Conclusions about spatial variability of precipitations in Nice

Finally, this analysis adds up to the conclusion that high temporal resolution of rainfall data is necessary to study urban hydrology phenomenon. The scale of the hour would be a maximum. Concerning the spatial resolution of rainfall data, the higher the better. When available, all rainfall stations should be taken into account.

The methodology proposed in this research work is built on the observations made in this part about the spatial variability of rainfall in Nice. Indeed, two study-cases are selected, one in the lower Var valley in the Saint-Augustin district, and the other one is the Magnan valley.

D.4. Comparison and relation between radar and rain gauge data

D.4.1. Principles and method

Rainfall radar data have been widely available. Nowadays this technology enables hydrologists to use high-resolution rainfall data.

This paragraph focuses on the comparison between radar data produced by the Mont Vial Radar operated by the company Novimet and rain gauge data belonging to the Nice Côte d'Azur Metropolis.

The goal of this analysis is to give information about the behaviour of both data sources compared to each other to improve local knowledge about rainfall data. The Météo-France data collected at Nice airport station is taken as a reference.

The main aspect to take into account is the time shift between the local data (given in French time, UTM+1 or 2 with seasonal change) and the radar data (given in UTM).

D.4.2. Rain Event on 04/11/2014 for Nice

Prior to any comparison, suitable rain gauges should be selected. Rain gauges which are unsuitable are the one with lacking data or the one uncovered by radar detection. The remaining rainfall stations are divided into three areas: the North part, the East part and the West part.



Figure 34. Display of rain gauges locations over radar data pixels

20-min-aggregation and 1-hour-aggregation have been tested to compare both sources of data. However, problems in the time reference have been encountered. No specific conclusion could raise from these first comparisons.

Next comparisons have been done following a daily aggregation for the November 4th 2014 event which produced flooding in Nice.


It appears that radar data globally under-estimate precipitations compared to rain gauges. Only station 23 shows a different situation with radar data over-estimating the gauge data. However, since time sliding issues have been seen at smaller time-steps, daily differences might be generated as well. After questioning, NCA Metropolis confirmed that their rain gauges were correctly set and checked.

D.4.3. Virtual rain gauges in the Magnan basin

Since October 2016, "virtual rain gauges" have been set-up in Nice. This means that the pixels of the radar data located at the rain gauges locations are selected and records are kept, for both real-time examination and historical analysis. Both data sources have been compared for two different events. First, rainfall data have been aggregated every 30 minutes for the October 14th 2016 event, secondly, every hour for the November 24th 2016 event.



(a)30-minute-aggregation, 14/10/2016

Figure 35. Graphs of the 14th October 2016 event

Table 7 presents the comparison of the cumulative values obtained from radar and rain gauge measurements for the 14th October 2016 event.

Cumulative values from 10h to 14h	Radar data (mm)	Rain gauge data (mm)	Difference in % of rain gauge data
Chalet des roses	53.7	29.6	81.4
La Costière	55.7	29.8	86.9
Aspremont	22.2	31	-28.4

Table 7. Comparison of rainfall data for a duration of 4 hours (14th October 2016 event)

For the two first stations "Chalet des roses" and "La Costière" the radar greatly overestimates by more than 80% rain gauge measurements. However, for "Aspremont" station, the radar underestimates by nearly 30% rain gauge data.



(b)1-hour-aggregation, 24/11/2016

Figure 36. Graphs of the 24th November event

Cumulative values are compared in Table 8 for the 24th November event.

Cumulative values from 02h to 08h	Radar data (mm)	Rain gauge data (mm)	Difference in % of rain gauge data
Chalet des roses	83.3	65.2	27.8
La Costière	79.9	87	-8.2
Aspremont	69.6	100	-30.4

Table 8. Comparison of rain gauge and radar data for the 24th November event

Differences in this case are lower than the previous case but still important. The "Chalet des roses" station shows an overestimation by nearly 30% while the "Aspremont" station is underestimated by 30%. "La Costière" station shows a difference smaller than 10% between radar and rain gauge data.

Conclusions about radar and rain gauge data in Nice

Further analysis with larger data sets or more events would be necessary to be able to conclude about the difference between rainfall data sources. Nevertheless, this first outline shows evidence that gaps exist and are not consistent with the time-steps whatever the amount of precipitation. Radar data should be used with care for Nice territory since significant over- and under-estimations were observed in both examined cases.

The methodology will prefer rain gauge data due to the lack of objectivity with the radar data utilisation.

Part E Spatial data

Spatial data used in this research work include topography, land use and drainage network data. Sources, features and main relevant information are presented in this part. The city of Nice has been developing in a complex geologic, geographic and demographic context. Almost 85% of the population is concentrated on the 25% of coastal stripes.

E.1. Topography and land use data

Topography data is available from the NCA Metropolis in different years of reference and different types. LiDAR data are available at a resolution of 5 m and 2 m and were captured in 2009. Most recent elevation data were captured during a campaign from 2010 till 2011 at a resolution of 50 cm by photogrammetry.



Figure 37. Globa view of digital elevation model provided by NCA Metropolis

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Figure 38. Example of topography data: photogrammetry digital elevation model with buildings polygons

Land use data is available from the European service CORINE Land Cover (http://land.copernicus.eu/pan-european/corine-land-cover).



Figure 39. Simplified geological map of Nice (Octobre 2011) (Source: Nice Côte d'Azur http://www.nice.fr/fr/prevention-des-risques/la-geologie-nicoise)

Western hills are mostly made of Puddingstone while eastern hills feature faults with contrasted geology.

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Figure 40. Main referenced hydrographic basins in Nice (source: <u>http://www.observatoire-eau-paca.org/commune/nice-576.html</u>)

The Var is the main river of the territory of Nice with a 2893-km²-watershed. It draws the western limit of the city. The Paillon is the second main river referenced in Nice with a 250-km²-watershed. The Paillon flows in the eastern part of the city and is covered at its downstream section in the city-centre area. The Var and the Paillon rivers are braided watercourses with changing geomorphology over the years.

The Magnan is the third main watershed of the hydrographic network with a drained area of 17 km². In the same way as the Paillon, it is covered at the downstream section as far as its outlet. The particularity of the Magnan is its low mean flow and the facts that it can be dried in summer seasons. Also, its outflow is drained to the sewer network in summer to protect the bathing water quality. The Magnan flows to the beach only in winter time.

E.2. Drainage network data

Main historical facts of the drainage system of Nice have been reviewed by the engineering consultant company SAFEGE in one of their reports (SAFEGE 2014). First dredging operations and channel constructions started in 1720. Open-sky sewers were covered in 1829. The current shape of the drainage system of Nice started to appear with the construction of the main drain from 1905 till 1912. At that time, the main interceptor drain collects all sanitary flows from the harbour to Carras district where the flow is driven to the sea. The drainage system was initially designed to be a sanitary drainage system, however starting in 1930, it has become gradually combined in the denser areas of Nice, where stormwater started to be collected. In 1936, the construction of the main pluvial aqueducts started. Later, the drainage system continued its evolution with a conception based on the technical instruction of 1977

which was the reference at that time. The wastewater treatment plant Haliotis was ready to operate in 1988. Nearby towns gradually added contributing areas and populations to the initial Nice drainage basin. Storage basins Arson (10 000 m³) and Ferber (30 000 m³) were built in 2006 and 2008 respectively.



Figure 41. Scheme of the Arson storage tank (NCA documentation)



Figure 42. Scheme of the Haliotis double storage tanks (NCA communication)

Nice is characterized by its alternating hills and valleys where the main pluvial aqueducts have been built, following the natural hydrographic network. The drainage network is mostly gravity-fed, due to the significant slopes of the terrain. Figure 43 displays the main features of the drainage and hydrographic networks. Sanitary and combined flows are driven by gravity to the coast where they are collected and directed from the East to the West part of the city, towards the Haliotis wastewater treatment plant.



Figure 43. Scheme of the main elements of Nice's drainage and hydrographic networks

As said previously, several surrounding towns are connected to this drainage network. Figure 44 presents the set of towns which have been connected to Nice's drainage network and driven to the Haliotis wastewater treatment plant up to now. This piece of information is extracted from (SAFEGE 2014).



Figure 44. Flowchart of the connected towns and their contribution to the Haliotis Basin (extracted from SAFEGE (2014))

The contributing population of the drainage system has raised from 357 421 inhabitants in 1968 to 488 299 inhabitants in 2009 (SAFEGE 2014). New connections of nearby towns started in 2006 with new connections in 2007, 2008, 2010 and 2014. Each new junction increases not only the population of the drainage basin but also the contributing drained area. The problem lies in the fact that the central historical drainage system is subject to increasing constraints while structures are aging and the whole network is complexifying.

Nowadays, network data are collected, centralized and regularly updated in the NCA Metropolis database. However, gaps exist in the description of the data. For example, even though the location and length of the pipes are correct, their diameter, material or type (sanitary, stormwater or combined) are sometimes lacking.



Urban drainage network in Nice area

Figure 45. Nice drainage network

Nice features 142 km of combined sewers, 379 of sanitary sewers and 250 of stormwater sewers.

Nice's network consists of the following hydraulic equipment:

- Sewer pipes
- Manholes, stormwater inlets and grates
- Sewer overflows
- Pumping stations
- Main interceptor drain and main drain
- Siphons
- Storage reservoirs (Arson and Ferber)
- Desanding basins

A specificity of Nice's drainage network management should be mentioned. Stormwater inlet baskets are widely used in the city to collect main waste elements from the street. An example is presented in Figure 46.

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Figure 46. Example of a stormwater inlet basket (Salvan, 2015)

The only available data regarding inlet baskets is the monthly weight of the collected waste in the whole city.

At the beginning of this research work, there were three operating companies of the drainage system in Nice:

- Lyonnaise des Eaux (Suez-Environnement) for the stormwater network ;
- SNA for the sanitary and combined network;
- Degremond (Suez-Environnement) for the wastewater treatment plant and the storage tanks operation and maintenance.

These private companies work for their client, the NCA Metropolis, which is a public structure. The coordination and concertation between these entities is crucial for the good operation of the whole system.

Since the original conception of the drainage network was based on the 1977 technical instruction and because of the intensive evolution of the city landscape and context, some difficulties are met in the drainage system which is globally efficient but prone to flooding in case of significant rainfall.

Part F Existing reports and modelling studies

Many studies and reports have been produced for the last decades, mostly written by consultant engineering companies in the framework of public market. Table 9 present the main relevant reports linked to the problematic of this research work. The global urban drainage model of Haliotis wastewater treatment plant has been built and updated accordingly, constantly evolving depending on the territory's needs, the modelling tools evolution and the measurement campaigns hold to enrich available datasets.

Table 9. List of existing reports belonging to NCA Metropolis related to Nice urban drainage and stormwater management (Titles are kept in French)

Title	Author	Year	Content
Caractérisation du réseau d'assainissement	Groupement SAFEGE	2000	 Main network structure Catchments Dry and wet weather contributions
Diagnostic préliminaire	Groupement SAFEGE	2002	 Hypotheses Diagnostic about pollution Diagnostic about flooding Specificities
Etudes préliminaires	Groupement SAFEGE	2002	Synthesis Phase 1
Calage du modèle du réseau d'assainissement	Groupement SAFEGE	2003	 Model update Dry weather calibration Wet weather calibration
Diagnostic des eaux parasites du réseau d'assainissement unitaire	Groupement SAFEGE	2003	Dry weather clear water infiltrations
Diagnostic RUTP	Groupement SAFEGE	2003	 Computation method of sewer overflow Dry weather diagnosis Wet weather diagnosis Impacts on receiving waters and related activities Directions for adaptation measures
Caractérisation RUTP	Groupement SAFEGE	2003	Pollution analysis

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Title	Author	Year	Content
Approche historique des crues de vallons niçois	Groupement SAFEGE	2003	Malvan, Magnan, Rivoli and Gambetta Valleys
Diagnostic inondation	Groupement SAFEGE	2003	Hydraulic dysfunctions Magnan, Rivoli and Gambetta Valleys
Diagnostic	Groupement SAFEGE	2003	Synthesis Phase 3
Etude du risque pluvial – Volet hydrologique	SAFEGE CETIIS	2004	Pluvial risk study (hydrology)
Etude du risque pluvial – Volet hydraulique	SAFEGE CETIIS	2004	Pluvial risk study (hydraulics)
Schéma directeur – Bilan du diagnostic	Groupement SAFEGE	2005	Phase 3 results and projection towards 2025
Schéma directeur – Lutte contre les inondations	Groupement SAFEGE	2005	Flood protection development proposals
Schéma directeur d'assainissement	Groupement SAFEGE	2005	Synthesis Phase 4
Dynamique fluviale du vallon Magnan	Hydratech-Asconit	2012	Magnan Valley fluvial dynamic
Modélisation de la pluie du 24 septembre 2012	SAFEGE	2013	Modelling of the September 24 th 2012 event
Etude hydraulique de modélisation des écoulements de temps de pluie sur le parcours de la ligne 2 projetée du tramway de Nice	SUEZ (SAFEGE)	2015	Overland flow hydraulic modelling on the projected tramway line 2

Those numerous reports show the classical process of a public need generating a tendering process and the selection of a company. The engineering company sets up a single study for

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the specific need and the report is provided to the metropolis. There is an urgent need to open again these single studies and to capitalise the information and conclusion made. New studies and further research would strongly benefit from a capitalising approach.

The Haliotis Basin drainage model was first built with MOUSE, the former version of Mike URBAN (DHI 2014b) and was later migrated to the new software version. Recent software evolutions do not impact the implementation of the model or its internal structure.



Figure 47. Global drainage system model of the Haliotis Basin built with Mike URBAN by SAFEGE, belonging to NCA Metropolis

This global model includes:

- 850 catchments;
- 320 km of pipes;
- 1 wastewater treatment plant;
- 11 CSO-connection structures "satellite" including offshore outfalls;
- More than 100 CSO;
- 30 pumping stations;
- 2 reservoirs (40 000 m³ in total);

- Real-time control (RTC) rules for automated devices.

The main phases of model evolution are the following:

- **2003:** Creation and calibration of the drainage network model.
- **2004:** pluvial risk analysis using a 1D-1D coupling system of the sewer network and the street network.
- **2011-2012:** Model update and implementation of new structure regulation rules, calibration with two events, validation with one event.
- 2012-2013: Study start about stormwater management for the Arenas district, modelling of the September 24th 2012 event and analysis of the model reaction to an extreme event using a coupled 1D-2D modelling system (only sewer overflow is considered).
- **2014:** Model update and modelling of the impact of new towns connections (Var left bank towns and main collector), study of the sewer overflow to receiving waters, measurement campaign allowing a model update and new calibration, especially of the outfalls.
- 2015: Study of overland flow hydraulic modelling on the projected tramway line 2 using a 1D-2D coupled system with one 1D sewer model and three 2D surface sub-models of three different areas of interest.

Reports written by SAFEGE present satisfactory qualitative calibration of the model with measurements, which was mostly the case in the different simulations performed during this research work. However, some irregularities have been identified, very often in link with errors in the data.

This model is used as a reference and as part of modelling systems in this thesis.

On the other hand, the PhD thesis of Jacques de Saint Seine (de Saint Seine 1995) should be mentioned as an important element of context. This thesis is dedicated to the hydrological and hydraulic study of the Paillon Basin. One of the practical interest was to implement a flood warning system to protect the drivers of a tunnel built in one of the arches of the covered Paillon riverbed. This flood warning system using a pre-alert step (depending on a precipitation threshold) and an alert step (depending on a discharge threshold) is still operational nowadays. Nine measurement stations are used in this system.

Following the same principle, NCA Metropolis wanted to implement a flood warning system for the Magnan Basin. Apart from its much smaller size, the Magnan River has several similarities with the Paillon River, especially its Mediterranean river regime and its covered and artificially channelized downstream section. Three measurement stations are available in the catchment however no operational warning system exist yet.

Part G Summary map of Nice city situation

Figure 48 presents the main information regarding measurement networks and urban drainage in Nice.



Situation of Nice area

Figure 48. Summary map of Nice

The denser city-centre area is characterised by the sensitive combined sewer network while main elements of the stormwater drainage network follows the natural hydrographic network. The complexity is the vulnerable coastal strip along the "Promenade des Anglais" which drains both the underground sewer flows, to drive them towards the Haliotis wastewater treatment plant, and the overland flow via the street network. Even with the building of two storage tanks for a total storage capacity of 40 000 m³, the centre of the city and downstream areas along the coast are vulnerable and prone to pluvial flooding, as well as sewer overflow, sometimes several times per year.

Part H Proposals and strategy to

improve measurements

Existing monitoring networks give useful information. However, they could be improved and other types of sensors could be implemented.

Improvements may be considered with three approaches:

- 1. Improve reliability of existing sensors
- 2. Add sensors to strategic points in existing monitoring network
- 3. Create new monitoring network or new intermittent use of new tools (CCTV, drone)

H.1. Rainfall measurements

Rainfall stations have proven to exist in a sufficient number in Nice's territory. With 21 stations in Nice and in its Vicinity for an area of 72 km², it makes sense to keep the existing stations without adding new ones. On top of that, two stations operated by Météo-France are available inside Nice's boundaries.

However, the recorded data suffer from gaps and errors. The actions that could be done are the following: to visit the stations regularly for maintenance aspects and to check connections towards data storage.

H.2. Hydrometric measurements

We have seen that hydrometric data include both river and drainage network measurements. Here the Var river is not included and its hydrometry is not presented. But two other rivers are concerned by this research work: the Magnan and the Paillon. On the other hand, hydrometric measurements are made in the underground network. In fact, the Magnan is almost considered as part of the drainage network.

Some gaps in the data could be avoided with more maintenance. Also, more measurement stations could benefit other studies and future research. Very often in the reported studies a measurement campaign is undertaken on a specific area for single needs. However, this specific data could benefit other studies. Easier access (for example online with an authorized account) would be useful.

Chapter 3 Methodology to model rainfall generated processes in urban areas

Part A Introduction

This chapter presents the material and methodology developed to model processes occurring in urban areas in rainy weather. This includes several aspects which are linked to the specificities of urbanization. After the state-of-the-art has been introduced in Chapter 1, and the main relevant information about Nice city, France, has been presented in Chapter 2, it is possible to propose a new approach.

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The main interest here is to innovate in the method using existing tools, rather than developing a new tool. The objective is to determine how to improve the use of existing models and tools, since in practice, it is not straightforward to move to a completely new tool for municipalities.

This thesis is included in a wider global research approach, as presented by Figure 49. This wider research approach can be defined as the successive steps starting with the observation of phenomenon that should be understood. Once the phenomenon is understood, the interest is to forecast is to be able to manage it.



Figure 49. Position of the thesis in a global research approach

When applied to the issue of stormwater management, this global approach starts with the observation of physical processes linked to precipitation leading to rainfall-runoff processes. The thorough understanding of such processes is a first condition to any management attempt.

The overall method covered the following sub-parts (Figure 50):

- Data and documentation collection: contact and meeting with local institutions and private engineering consultancy to build the picture of the state of knowledge and local issues.
- Strategy definition: brain-storming based on data and documentation confronted to the scientific review of the state of the art.
- Modelling and uncertainties analysis: set-up of modelling system to simulate rainfall events and their consequences in urban areas of Nice.
- Rainfall regime analysis: analysis of local rainfall data sources and determination of the gaps.
- **Topographic delineation and selection of districts:** analysis of local topography data and choice of areas of interest based on the available data and the local issues.
- Analysis of sewer overflow to the Mediterranean Sea: characterization of the sewer overflow to the sea depending on rainfall conditions.
- Analysis and reflection towards further research: analysis of the results and perspectives and insights for further research or study in the same domain and/or location.



Figure 50. Main sub-topics of the approach

Part B Research steps of overall modelling method

This research work is built on a will to improve local knowledge in a wide extent, with an exploration point of view. This explains the diversity of different aspects that are raised and discussed. A complex topic necessarily leads to several important interconnected aspects. In the literature, many authors chose to address these aspects separately. This is needed, however not sufficient to get the global image of the problematic. This is the reason why the strategic bias here is to address main aspects together and to highlight their most important principles and connections. The downside is the difficulty to completely develop all aspects together with the same level of detail. This work gives foundations for further research in the same geographical type of study-case or in the same scientific domain.



Figure 51. Modelling scope of the approach

Part C Modelling tools

Modelling tools used nowadays are based on computational hydraulics and applied hydrology of which basics and principles have been published for several decades (Chow 1959; Abbott 1979; Chow 1988). In this research work framework, the selection of computational tools has been made according mainly to the already used model in the NCA metropolis, the DHI suite of software. Mike URBAN is used as the 1D modelling tool, while Mike 21 is used for 2D simulations. Mike FLOOD is the DHI module allowing coupled simulations between Mike URBAN and Mike 21, among other types of coupling possibilities. For comparison reasons, some 2D simulations have been performed with the free numerical code FullSWOF-2D.

C.1. Mike URBAN

Mike URBAN (DHI 2014b) is an urban water modelling software able to model 1D water networks. Typical applications are drinking water and drainage systems. Drinking water engine is based on the numerical engine EPANET (L. a Rossman 2000) (public domain EPANET engine developed by EPA, US). Regarding collection systems, the user can choose between two numerical engines: the SWMM5 (Lewis A Rossman 2015) engine (developed by EPA, US) and the MOUSE engine. Mike URBAN simulations depend on several interacting modules (Figure 52).



Figure 52. The modular structure of Mike URBAN (extracted from (DHI 2014b))

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C.1.1. Pipe flow module

Mouse engine is able to model hydrology and hydraulics in both open and closed conduits, including water quality and sediment transport. Hydrodynamic simulations can be done to simulate unsteady flows and water levels in stormwater, sanitary and combined pipe systems. Alternating free surface and pressurised flow conditions are supported. Computations are based on an implicit, finite difference numerical solution of the 1D shallow water equations, the Saint-Venant system (De Saint-Venant 1871) including the conservation of mass and the conservation of momentum (Equations 1 and 2).

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = 0 \tag{1}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial \left(\alpha \frac{Q^2}{A}\right)}{\partial x} + gA \frac{\partial y}{\partial x} + gAI_f = gAI_0$$
⁽²⁾

where:

Q = discharge, [m ³ s ⁻¹]	t = time, [s]
A = flow area, [m²]	α = velocity distribution coefficient
y = flow depth, [m]	I_0 = bottom slope
g = acceleration of gravity, [ms ⁻²]	I_f = friction slope

x = distance in the flow direction, [m]

In MOUSE, the Saint-Venant equations (De Saint-Venant 1871) are implemented using the same notations as follows:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = 0 \tag{3}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial \left(\alpha \frac{Q^2}{A}\right)}{\partial x} + gA \frac{\partial y}{\partial x} = gA(I_0 - I_f)$$
⁽⁴⁾

These equations are valid for free-surface flow as described in Figure 53.

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Figure 53. Scheme of a pipe section (reproduced from DHI (2014))

The continuity equation expresses that the volume of water, ∂Q , which is added in pipe section of length ∂x , is balanced by an increase in cross-sectional area ∂A (storage). The first two terms on the left side of the momentum equation represent the inertia forces (local and convective acceleration), while the third term represents pressure forces. The two terms on the right-hand side of the equation represent gravity and friction forces, respectively.

The implemented algorithm solves the flow equations by an implicit finite difference method. Setting the numerical scheme into the frame of the Double-Sweep algorithm ensures preservation of the mass continuity and compatibility of energy levels in the network nodes.

In all pipes and canals the computational grid is set up in an alternating sequence of h- and Q-points. In these grid points the discharge Q and water level h, respectively, are computed at each time step. The links (pipes and canals) will always be setup with h-grid points at each end where the link connects to nodes in the network. This means that links will always have an odd number of computational grid points with three points (h - Q - h) as the mini-mum configuration.



Figure 54. Computational grid (extracted from (DHI 2014b))

The implemented numerical scheme is a 6-point Abbott-scheme (Abbott 1979).



Figure 55. Centring of the continuity equation in the Abbott scheme (Abbott 1979) (extracted from (DHI 2014c))



Figure 56. Centring of the momentum equation in the Abbott scheme (Abbott 1979) (extracted from (DHI 2014c))

The pressurised flow can be modelled considering that at the moment the full flow capacity is reached, the flow depth is equal to the conduit height. Any increase of discharge transforms the flow conditions. To cover the pressurised flow conditions and generalise the equations of free surface flow, a fictitious slot, known as the "Preissmann slot", is introduced in the top of the conduit. The idea of this method was first introduced by Preissmann & Cunge (1961) and applied by J. A. Cunge & Wegner (1964). Recent explanations can be found in the book of Butler & Davies (2010).



Figure 57. The Preissmann slot scheme with D, diameter of the sewer pipe, B the width of the slot (reproduced from DHI (2014), *after* (Preissmann and Cunge 1961))

In order to obtain a smooth transition between the free surface flow computations and pressurised flow computations, it is required to apply a "soft" transition between the actual pipe geometry and the fictitious slot. Such a "smooth" transition has been designed based on a series of tests with various slot configurations. The slot configuration thus obtained ensures stable computations without affecting the accuracy significantly. The applied slot width is larger than the theoretical value.

Since both nodes and pipes can have Preissmann slots that emulate pressurized nodes or pipes, it often happens that there is flooding in the system but not spilling. Thus, flooding does not necessarily mean that there is water running out of the system onto the ground.

If the water level in a manhole or a basin reaches the ground level, an artificial "inundation" basin is inserted above the node. The surface area of this basin is gradually (over one meter) increased from the area in the manhole or the basin to a 1000 times larger area, thus simulating the surface inundation. The maximum level of inundation is 10 m above the specified ground level. When the outflow from the node surmounts the inflow, the water stored in the inundation basin re-enters the system. The shaded area in Figure 58 illustrates the generated volume of water as soon as the water level exceeds the transition region between the actual manhole and the artificial basin.



Figure 58. Simulation of the surface flooding (DHI 2014c)

For the finite difference scheme, the Courant condition (C_r) is a stability criterion, from which the velocity condition is originated (6).

$$C_r = \frac{\Delta t \left(v + \sqrt{gy} \right)}{\Delta x}$$

$$v \cdot \Delta t \le \Delta x$$
⁽⁵⁾
⁽⁵⁾
⁽⁵⁾
⁽⁶⁾

With:

v: mean flow velocity (ms⁻¹)

 Δt : time step (s)

 Δx : distance between computational points in the conduit (m)

y: water depth (m)

Head losses caused by the resistance in free-surface flow links are introduced as a friction slope term into the momentum equation. The friction slope If is equal to the slope of the energy grade line.

$$I_f = \frac{\tau}{\rho g R} \tag{7}$$

With:

 τ : tangential stress caused by wall friction (Nm⁻²)

```
ρ: water density (kgm<sup>-3</sup>)
```

```
R: hydraulic radius (m)
```

More details can be found in the manual (DHI 2014c).

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C.1.2. Hydrology module

In Mike URBAN, rainfall-runoff transformations can be computed with four different runoff model concepts within a lumped framework:

- Model A: Time-area method
- **Model B:** Non-linear reservoir method (kinematic wave)
- Model C: Linear reservoir method, including two sub-types:
 - Model C1: Dutch runoff model
 - Model C2: French runoff model
- UHM: Unit hydrograph model

Each model concept requires specific catchment data. The model user must choose only one model concept for all catchments per simulation. General catchment data are independent of the selected runoff model. Parameter sets can be created to define model parameters.

In the context of this thesis, only the Model C2 is used and described here. Information about other runoff models can be found in the manual (DHI 2014d).

The surface runoff computation of MOUSE Runoff Model C is founded on the routing of the runoff through a linear reservoir. This means that the surface runoff from a catchment is made proportional to the current water depth on the catchment. The runoff amount is controlled by the initial losses, size of the actually contributing area and by infiltration losses. The shape of the runoff hydrograph (phase and amplitude) is controlled by the catchments time constant.

Model specific data for catchments are:

- **Impervious area [%]** fraction of the catchment area, considered to contribute to the runoff.
- **Length [m]** Catchment length, used in the empirical calculation of the catchments lag time constant. Represents the estimation of the maximum runoff length from the periphery of the catchment to the point of connection.
- **Slope [‰]** Catchment slope, used in the empirical calculation of the catchments lag time constant. Represents the estimation of the average runoff slope.

The hydrological parameters are the following:

- **Initial Loss** - defines the precipitation depth, [m], required to start the surface runoff. This is a one-off loss, comprising the wetting and filling of catchment depressions.

The MOUSE default value is 5.00E10-4 m.

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- **Time lag** - the linear reservoir time constant (min), controls the shape of the runoff hydrograph (reaction time).

The MOUSE default value is 5.0 min.

- **Infiltration - maximum capacity (mm/h)** - defines the maximum rate of infiltration (Horton) for the specific surface type.

The MOUSE default value is 2.00 mm/h.

- **Infiltration - minimum capacity (mm/h)** - defines the minimum rate of infiltration (Horton) for the specific surface type.

The MOUSE default value is 0.50 mm/h.

- **Infiltration - time coefficient (wet conditions) (1/h)** - time factor "characteristic soil parameter" [s⁻¹]. Determines the infiltration capacity rate reduction during rainfall.

The MOUSE default value is 3.00 h⁻¹.

- **Infiltration - time coefficient (dry conditions) (1/h)** - time factor used in the "inverse Horton's equation", defining the rate of the soil infiltration capacity recovery after a rainfall, i.e. in a drying period.

The MOUSE default value is 0.10 h⁻¹.

 Reduction factor – accounts for various hydrological losses not accounted explicitly in the computation.

The MOUSE default value is 0.90.

The runoff model C computations are based on the volume continuity and the linear reservoir equations. The first step is the calculation of effective precipitation intensity. The effective precipitation intensity is the precipitation, which contributes to the surface runoff. Next, the hydraulic routing based on the linear reservoir principle and volume continuity is applied.





Figure 59. Simulated processes in the runoff model C2 in Mike URBAN (reproduced from (DHI 2014d))

The simulated hydrology processes aim to compute the effective precipitation ($I_{eff}(t)$) which is the remaining precipitation after abstraction of the losses such as evaporation, infiltration and surface storage.

$$I_{eff}(t) = I(t) - I_E(t) - I_I(t) - I_S(t)$$
(8)

where:

I(t) = Actual precipitation intensity at time t,

 $I_E(t)$ = Evaporation loss at time t. It should be noted that the evaporation loss for the catchment is accounted only if the RDI runoff computation is activated. Otherwise, it is replaced by a constant "decay" rate.

 $I_{s}(t)$ = Initial loss (wetting and surface storage) at time t,

 $I_{I}(t)$ = Infiltration loss at time t.

The individual terms in the loss equation are fundamentally different, as some terms are continuous where others are discontinuous. If the calculated loss is negative, it is set to zero. The losses have a dimension of velocity [LT⁻¹].

The actual precipitation, I(t), is assumed to be uniformly distributed over the individual catchments. Otherwise, it may vary as a random time function.

The evaporation, $I_E(t)$, is a continuous loss that is normally of less significance for single event simulations. However, on a long-term basis, evaporation accounts for a significant part of hydrological losses.

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The infiltration, $I_{l}(t)$, is the water loss to the lower storage caused by the porosity of the catchment surface. It is assumed that the infiltration starts when the wetting of the surface has been completed.

The surface storage, $I_S(t)$, is the loss due to wetting and filling the depressions and holes in the terrain. The model begins with the surface storage calculation after the wetting process is completed. The surface storage is filled only if the current infiltration rate is smaller than the actual precipitation intensity reduced by evaporation.

The runoff starts when the effective precipitation intensity is larger than zero. The hydraulic process is described with the linear reservoir equation. The surface runoff at time t is calculated as:

$$Q(t) = C y_R(t) \tag{9}$$

where:

C = Linear reservoir constant,

 $y_{R}(t) = Runoff depth at time t.$

The depth $y_R(t)$ is determined from the continuity equation:

$$I_{eff}(t)A - Q(t) = \frac{dy_R}{dt}A$$
⁽¹⁰⁾

where:

 I_{eff} = Effective precipitation,

A = Contributing catchment surface area,

dt = Timestep,

 dy_R = Change in runoff depth.

The linear reservoir constant C =1/K is calculated as:

$$C = \frac{A}{T_L} \tag{11}$$

where:

A = Total catchment surface area,

 T_L = Catchment lag time.

More details can be found in the manual (DHI 2014d).

C.2. Mike 21

To perform coupled simulations between sewer flow and overland flow, it is possible to use a 1D representation of the sewer system with Mike URBAN (DHI 2014b), as seen previously. Then the overland flow can be modelled with Mike 21 (DHI 2016a) and both models can be coupled via Mike FLOOD (DHI 2016c). This paragraph presents in details the 2D modelling tool Mike 21 (DHI 2016a).

Mike 21 (DHI 2016a) is a numerical modelling system able to simulate 2D unsteady flows and water levels in one layer which is vertically homogeneous. Hydrodynamic simulations can be carried out by solving the 2D shallow water equations of mass and momentum. Flow can be modelled by the Navier-Stokes equations and their most used simplifications are the 2D Shallow Water Equations (2D-SWEs), which are valid under the following conditions (Hardy, Bates, and Anderson 1999; Horváth et al. 2015):

- water is incompressible and homogeneous;
- velocity components in the vertical direction are negligible;
- pressure distribution is hydrostatic in the vertical direction;
- bottom slope is small;
- friction terms (viscosity, bottom and free surface friction) can be represented by empirical expressions from steady flow studies.

Equations below describe the conservation of mass and momentum integrated over the vertical with the flow and water level variations.

$$\frac{\partial \zeta}{\partial t} + \frac{\partial p}{\partial x} + \frac{\partial q}{\partial y} = \frac{\partial d}{\partial t}$$
(12)

$$\frac{\partial p}{\partial t} + \frac{\partial}{\partial x} \left(\frac{p^2}{h}\right) + \frac{\partial}{\partial y} \left(\frac{pq}{h}\right) + gh \frac{\partial \zeta}{\partial x} + \frac{gp\sqrt{p^2 + q^2}}{C^2 h^2} - \frac{1}{\rho_w} \left[\frac{\partial}{\partial x}(h_{\tau xx}) + \frac{\partial}{\partial x}(h_{\tau xy})\right] - \Omega q$$

$$- fVV_x + \frac{h}{\rho_w} \frac{\partial}{\partial x}(P_a) = 0$$

$$(13)$$

$$\frac{\partial q}{\partial t} + \frac{\partial}{\partial y} \left(\frac{q^2}{h}\right) + \frac{\partial}{\partial x} \left(\frac{pq}{h}\right) + gh \frac{\partial \zeta}{\partial y} + \frac{gq\sqrt{p^2 + q^2}}{C^2 h^2} - \frac{1}{\rho_w} \left[\frac{\partial}{\partial y} (h_{\tau yy}) + \frac{\partial}{\partial x} (h_{\tau xy})\right] - \Omega p$$

$$- fVV_y + \frac{h}{\rho_w} \frac{\partial}{\partial y} (P_a) = 0$$
⁽¹⁴⁾

Where:

h(x,y,t): water depth (m)

d(x,y,t): time varying water depth (m)

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$\zeta(x,y,t)$: surface elevation (m)

p,q(x,y,t): flux densities in x- and y_directions (m³/s/m)

C(x,y): Chezy resistance (m^{1/2}/s)

g: acceleration due to gravity (m/s²)

f(V): wind friction factor

V, V_x , $V_y(x,y,t)$: wind speed and components in x- and y-directions (m/s)

 $\Omega(x,y)$: Coriolis parameter, latitude dependent (s⁻¹)

 $p_a(x,y,t)$: atmospheric pressure (kg/m/s²)

 ρ_w : density of water (kg/m³)

x,y: space coordinates (m)

t: time (s)

 T_{xx} , T_{xy} , T_{yy} : components of effective shear stress

2D Shallow Water equations, also called Saint-Venant equations (De Saint-Venant 1871), are described by the following mass and momentum conservations:

$$\begin{cases} \partial_t h + \partial_x (hu) + \partial_y (hv) = P - I \\ \partial_t (hu) + \partial_y (huv) + \partial_x \left(hu^2 + g \frac{h^2}{2} \right) = gh(S_{0x} - S_{fx}) \\ \partial_t (hv) + \partial_x (huv) + \partial_y \left(hv^2 + g \frac{h^2}{2} \right) = gh(S_{0y} - S_{fy}) \\ with S_{0x} = -\partial_x z(x, y) \text{ and } S_{0y} = -\partial_y z(x, y) \end{cases}$$
(15)

Where :

gravitational constant (m/s²), g

P(t, x, y)rainfall intensity (m/s),

I(t, x, y)infiltration rate (m/s),

 $\vec{S}_f = (S_{fx}, S_{fy})$ roughness term (depending on the roughness law),

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z(x, y) topography (m).

Mike 21 uses the Alternating Direction Implicit (ADI) technique to integrate the equations for mass and momentum conservation in the space-time domain. This technique is a finite difference method (Danish Hydraulics Institute 2016). The equation matrices that result for each direction and each individual grid line are resolved by a Double Sweep (DS) algorithm. The domain is designed as a structured rectangular mesh.

In the 2D models used to compute the water depth, some thresholds are implemented to reduce the simulation time by activating/deactivating the cells included in the computation process. Especially with DHI software tools, flooding and drying depth are used as rules for saving calculation time. These parameters regulate the number of cells which is considered to solve the SWEs. In Mike 21, a flooded cell is a cell which has a water depth greater than the flooding depth. In contrast, a dry cell is a cell which has a water depth less than drying depth, but can contain water because of the EPSF, name of the minimum water flooding depth parameter, (=0.0002 m) representing the minimum water depth. This value is automatically affected in case of dry cell and causes a violation of the mass-balance. The threshold function used in Mike 21 is described by three cases (Danish Hydraulics Institute 2016): flooding due to accumulation of water from an external source (precipitation, source), flooding due to high water level in neighbour-cells, and drying case. The first one considers each dry cell with an initial water depth of 0.0002 m (EPSF default value). The process adds the accumulated water depth, from an external source to the EPSF value in each cell until being above the flooding depth. When this happens, the motion and the drying process can be applied. The second one takes into account the neighbour-cells. Indeed, this process is the flow principle from a higher point to a lower point. The last one is a checking process which is able to qualify that a cell should go from wet to dry, and thus does not apply the equation of motion. A new parameter, EPSH (the very small water depth), defines the extreme limit to dry a cell. If the water depth is between the EPSH value and the drying depth, the neighbour-cells are checked to know if the transfer of water is possible from one cell to another. Figure 60 summarises the flooding and drying parameters used in Mike 21 and the default values defined by DHI.

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Figure 60. Flooding and drying parameters and corresponding default values defined by DHI in Mike 21 (DHI) (extracted from (Leslie Salvan et al. 2017))

More details can be found in the manual (DHI 2016a).

Another 2D software tool is made available by DHI: Mike 21FM (DHI 2016b). Using a finite volume method, the user can choose the time integration between two options: lower order method which is the first order explicit (with a Roe scheme) or higher order method which is the second order, Runge-Kutta, method. In both cases, the convection flux is computed with a Roe numerical solver (Roe 1981) and a TVD slope method is used to minimize oscillations (Darwish and Moukalled 2003) and to perform a second order in space. Moreover, the geometry can be designed with triangular or quadrangular cells (qualified as flexible mesh by DHI).

However, Mike 21 is chosen here for different reasons. First, the implementation of unstructured mesh could be seen as an advantage to reduce the number of computational points in the model domain; however in urban cases, only very limited areas do not need specific refinement. Indeed, urban furniture might be located everywhere in the domain and flexible mesh would be more beneficial in fluvial cases. Secondly, this flexible mesh has one main objective, which is to reduce the computational cost of the simulations. But since the mesh size will be substantially the same everywhere in the domain, there might be no computation time reduction at all. Third, the engineering time is much less important using Mike 21 (for which the topography grid can be used directly in the model) than using Mike 21FM (for which mesh building can take a significant time).

C.3. FullSWOF-2D

The 2D SWEs based code FullSWOF_2D (Full Shallow Water equations for Overland Flow) is developed as a free software in C++ (O. Delestre et al. 2012; Olivier Delestre 2010) where the 2D SWEs are solved using a well-balanced finite volume scheme based on the hydrostatic reconstruction (Olivier Delestre 2010).

The finite volume scheme is applied on a structured spatial discretization using regular Cartesian meshing. The hydrostatic reconstruction (which is a well-balanced numerical strategy) allows to ensure that the numerical treatment of the system preserves water depth positivity and does not create numerical oscillation in case of a steady state, where pressures (in the flux) are balanced with the source term (the topography).

A variable time step is used for the temporal discretization based on the CFL criterion (fixed to 0.45). Computations were run using the MPI parallel version of the code over 64 CPU. A second order scheme is used with a HLL solver (Bouchut 2004).

This software has been used to a limited extent since it was developed for rural areas.

C.4. Mike FLOOD and surface-sewer coupling

Mike FLOOD (DHI 2014a) is a modelling tool which integrates the one-dimensional models Mike URBAN (with the MOUSE engine), Mike HYDRO River, Mike 11 and Mike 21 into a single, dynamically coupled modelling system. Coupling of the different models are made through different linkage options. Seven different types of links are presently available in MIKE Flood:

- 1. Standard Link
- 2. Lateral Link
- 3. Structure Link
- 4. Side Structures Link
- 5. Zero Flow links ($X_{Flow}=0$ and $Y_{Flow}=0$)
- 6. Urban Link
- 7. River-Urban Link

Link types 1 to 5 above concern the coupling of MIKE 11 and MIKE 21, Link type 6 is designed for linking MIKE URBAN with one or more cells/elements in MIKE 21 and finally, Link type 7 is reserved for linking the river network (MIKE 11) with the collection system (MIKE URBAN). Only the urban link will be described in this part as others were not used. Figure 61 presents the file structure used in the coupling between Mike URBAN and Mike 21. The respective project files are linked through a file with the termination ".couple" of Mike FLOOD. The choice of the computational time-step is done within the Mike 21 interface.



Figure 61. Scheme of the coupled modelling system with corresponding file types and software tools

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C.4.1. Urban links

The urban link is designed to describe the interaction of water when a manhole is overtopped or when overland flow enters a sewer/storm water network.



Figure 62. Flooding from the overland flow (Mike 21) into a non-surcharged sewer system (Mike URBAN) (reproduced from (DHI 2014a))

The urban link may also be used for linking a sewer outlet with the overland topography. This may be used to describe the dynamic interaction between a sewer system and a collection basin described using the topography as opposed to describing the basin using an area elevation curve. Finally, the link is also applicable to situations where the sewer system is discharging into the surrounding area through a pump or over a weir. In these cases, the pump or the weir must be defined as having no downstream node.



Figure 63. Flooding from a surcharged sewer system (Mike URBAN) to the surface (Mike 21) (reproduced from (DHI 2014a))

The link is designed such that one or more cells/elements in MIKE 21 may be linked to a manhole, basin, outlet, pump or weir in MIKE URBAN(MOUSE).

The exchange of water (QUM21) at the inlet can be computed in three different ways:

- Orifice equation
- Weir equation
- Exponential function

C.4.2. Orifice equation

The orifice calculation is given by:

$$Q_{UM21} = sign(H_U - H_{M21})C_D Min(A_m, A_I)\sqrt{2g|H_U - H_{M21}|}$$
(16)

for $|Q_{UM21}| < Q_{max}$

Where:

 Q_{UM21} : Flow from sewer to MIKE 21 grid point.

H_U: Water level in sewer system.

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 H_{M21} : The average water level on the ground.

A_m: Cross-sectional area of manhole.

A_l: Cross-sectional area of inlet (not used for basins) and

C_D: The discharge coefficient (typically 1).

Note that if the nodes ground level is greater than either the water level in the node or the water level in MIKE 21 then the corresponding water level is overridden by the ground level.

C.4.3. Weir equation

The weir equation depends on whether there is flooding on the surface or not. If the surface is not flooded at the time, then it is calculated as a free-flowing weir:

$$Q_{UM21} = C(H_U - H_{M21})W_{crest}\sqrt{2g|H_U - H_{M21}|}$$
(17)

for $|Q_{UM21}| < Q_{max}$

Where:

W_{crest}: crest width to be used in the equation

The same equation is used if surface is flooded and the water level in the node is below the nodes ground level. If the surface is flooded (water level in MIKE 21 and MIKE URBAN above the nodes ground level) then the weir is calculated as a submerged weir:

$$Q_{UM21} = C(H_U - H_{M21})W_{crest}\sqrt{2g|H_U - H_{M21}|} \left(\frac{|H_U - H_{M21}|}{\max(H_{M21}, H_U) - H_g}\right)$$
(18)

Where:

H_g: ground level at the coupling

C.4.4. Exponential function

The last function for computing the flow between MIKE URBAN(MOUSE) and

MIKE 21 is given by:

$$Q_{UM21} = sign(H_U - H_{M21})S(|\max(H_{M21}, H_g) - \max(H_U, H_g)|)^{Exp}$$
(19)

for $|Q_{UM21}| < Q_{max}$

Where S is the Scaling factor and Exp the Exponent.

More details and other components can be found in the manual (DHI 2014a).

C.4.5. Stormwater inlet representation in Mike URBAN

In Mike URBAN, stormwater inlets can be modelled by two methods. One way would be to combine orifices and weirs to create structures comparable to side pits and grates. Another way consists in using a specific object created to represent stormwater inlets: the "curb inlet" object.

The curb inlet object incorporates the geometry of the inlet structure.

C.4.6. Surface-sewer coupling within the Mike URBAN interface

For simple cases or model users willing to work in only one interface, there are two possibilities to couple overland and sewer flow within Mike URBAN.

The first method consists in adding a raster DEM to the network layout to model the surface of the studied area. In this way, a 1D-2D coupling can be implemented using the same equations and parameters than presented previously with Mike FLOOD. However, only structured rectangular mesh can be used.

The second method uses a 1D-surface network to implement a 1D-1D coupling system. This means that the surface flow path should be known, as overland flow would be limited to this surface network.

C.4.7. Summary

Table 10 presents the available parameters in each coupling flow computation method. On the other side, it is also possible to check with parameters should be set when choosing a coupling method.

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Table 10 Description of the parameters and options of urban links in MIKE FLOOD (DHI) in relation with the flow calculation methods

		Flow calculation				
		Orifice equation	Weir equation	Exponential function	Curb inlet function	
	Max flow	Х	Х	Х	X	
S	Inlet area	Х				
arameters / Option	Crest width		Х			
	Discharge coefficient	Х	x			
	Scaling factor			Х		
	Exponent factor			Х		
	QdH factor	Х	Х	Х	X	
	Freeboard				Х	
۵	Capacity curve DQ relation				Х	

This table shows that all coupling method require the same number of parameters or options to be filled. However, most parameters are dedicated to one method. The parameter "maximum flow" and the option "QdH factor" are the only transversal ones.

The maximum flow should be estimated by the modeller from its structure knowledge.

There is an option to suppress oscillations by use of the QdH factor. The value corresponds to the water level difference below which the suppression is applied. The suppression is designed for cases where the pressure level in the sewer system is close to the water level in MIKE 21 and may be applied individually at each urban coupling. If a value of 0.0 is given then no suppression is applied. When another QdH value is given, the discharge is multiplied by a suppression factor between 0 and 1. When the water level difference between the node and MIKE 21 is greater than Qdh then the factor is 1. For water level differences dh less than QdH, the sup-pression factor is:

Suppression factor =
$$1 - \left(\frac{QdH - dh}{QdH}\right)^2$$
 (20)

Part D Overland flow and topography data

D.1. Background

Urban flash floods generated by extreme rainfall events are devastating for populations, assets and city functions. As the urban population is worldwide developing, the risks and their consequences are dramatically increasing. On top of that, sewer systems are very often not proportionally developed to comply with much greater volumes generated by urban expansion. There is therefore a high need for stormwater management, which requires accurate and efficient modelling or methods to quickly give indicative results for population and asset protection.

Urban systems have a double drainage system: surface runoff over streets and underground pipe network which are interacting during rain events. Interactions between overland flow and sewer pipe flow are complex to observe and to model. The interest to take these interactions into account has been studied using different methods (Djordjević et al. 2005; Chen et al. 2007; Beniamino Russo et al. 2015; Chang, Wang, and Chen 2015). However, in an operational framework, in case of a heavy rainfall event, sewer systems can be considered as unavailable. Indeed in practice, because interactions are not well-known and due to grate clogging occurrence, surface runoff can be seen as the most critical contribution to flooding (ASN 2013).

Another source of complexity for urban flood assessment relies in urban topography and geometry. Urban surface features ranging from macro features (*e.g.* building), to micro features (*e.g.* sidewalks, road curbs, *etc.*), have been included in flood modelling approaches for various urban hydrology and flood assessment purposes (J. Leandro, Schumann, and Pfister 2016; Chen et al. 2012; Schubert and Sanders 2012; Schubert et al. 2008). However, the implications of high-resolution data use combined with optimisation procedure for operational 1D-2D urban drainage modelling have not been studied so far.

This part focuses on the effects of detailed urban geometry on flow paths assessment as it affects in the same time overland runoff and buried pipe flow properties. The aim is to carry out an analysis of the impact of the level of detail of urban above-ground features taken into consideration when assessing catchment drainage. The first question to be raised is indeed how buildings and urban features divert overland flow. As a consequence, the implications for urban flood modelling have to be defined. The second topic raised by this paper is the potential possible simplifications for model building, *i.e.* which level of details is needed to set up a suitable model that is fast and accurate enough to enable operational modelling in order to help sewer operators and risk planners.

D.2. Modelling approach

The method is synthesised in Figure 64. To perform this study, a small urban catchment is chosen according to available HR data for the region. Suitable data is composed of evolving information with gradual levels of complexity, starting from a raw Digital Terrain Model (DTM) as basis to DEMs including as many details as possible (S1 to S4 in Figure 68). Here a photo-interpreted dataset is used. Interest of this type of dataset for hydraulic community is that it allows to build a HR DEM encompassing fine features which can be selected for its purpose, depending on the level of complexity of features that the modeller judges relevant to include (Morgan Abily et al. 2013; M. Abily et al. 2016).



Figure 64. Overview of the applied methodology

In this part, four different levels of surface feature information are selected for the study-area (S1-4). Their content has been selected from the available classification of features that has been considered as introducing complexity in surface drainage paths. The classes of selected features (under the vector form) are extruded on the DEM at a 1m-resolution.

Figure 64 presents the flow chart of the overall approach. As a first step, a GIS analysis is performed on the different defined DEMs S1-4. The results will be compared. The second step consists in a 1D-simulation of the sewer network of the city for the selected event. In parallel, 2D simulations are performed with the objective to confront static observations with dynamic results.

Part E Pipe and overland flows in interaction

E.1. Background and objectives

This part is the second step of the modelling approach. The focus here is on the modelling of network spillage and the interactions between the sewer flow and the overland flow when the drainage network overflows.

Comparable analyses have been conducted in Nice (SAFEGE 2015; Corre, Parcé, and Sanson 2016). SAFEGE has been asked to perform a study of flood risk for the new line of tramway the construction of which is ongoing. In their study, the 2D surface model is built with an unstructured triangular mesh using finite-volume method. The global drainage network model of the Haliotis basin is used. Three different 2D sub-models are created to study three areas of interest along the planned new tramway line.

The objective here is to perform a 1D-2D coupling using a structured rectangular mesh and finite-difference method to test its efficiency and potential limits.

E.2. Modelling system

The modelling approach relies on the coupling of a 1D sewer network model with a 2D surface model. The sewer network model is built with Mike URBAN (DHI 2014b) while the surface model is built with Mike 21 (Danish Hydraulics Institute 2016). The coupling is operated with Mike FLOOD (DHI 2016c). Figure 65 presents the file and software architecture. It should be noticed that the computational time-step is selected within Mike 21 interface.



Figure 65. Modelling approach of sewer-overland flow interactions

Part F Integrated urban pluvial modelling

F.1. Context of suburban catchments

By "suburban areas" we define here districts located at the outskirts of a city and characterized by sparse urbanization in contrast with dense inner city which can be called "urban areas". However, the existence of built-up parts and the vicinity of the city do not allow to define them as "rural areas". Very often these zones have been developing in the background of urban expansion and integrate mixed activities and land uses. Furthermore, "suburban catchments" in the context of urban hydrology imply specific issues related to the diverse included activities and the Mediterranean location. Indeed, this type of catchment is very often composed of an upstream hilly part with steep slopes draining to a rather flatter urbanized area. Several similar cases can be found in Mediterranean cities located between mountains and sea (e.g. Marseilles, Nice, Genoa, etc.). It is thus easy to understand that the downstream area and its population and activities are at risk in case of heavy rainfall, especially considering very quick response time. There is therefore a need for a better understanding of the physical processes to improve their modelling to ensure the set-up of a fast and reliable warning system for such kind of districts.

Misunderstanding often leads to wrong management. When dealing with urban stormwater, understanding the physical processes involved is crucial to adequately conceptualize their representation within decision supporting tools. It is a prerequisite for an effective assessment and management of the urban stormwater system. Standard concepts are well known [1]: a rainfall event begins as precipitation starts. The surface of the city (i.e. roofs, streets and green areas) is gradually wetted until the quantity of water accumulates enough to runoff following the flow paths defined by the urban topography. Regarding drainage, urban areas can be divided into a major and a minor system that are interacting under rainy weather [2]. This dual system can be seen as an analogy of a river system regarding the riverbed and the floodplains. The minor drainage system is in fact the designed system which should contain stormwater in normal operation. The major system is the street network and the overland space which is flooded in case of failure of the minor system. Different cases of failure may be encountered like sewer overflow or inlet clogging. The framework of the research presented in this paper lies in the better understanding of urban pluvial flood modelling concepts. This leads to the aspects of topography and rainfall and their suitable representation in urban areas to enable a coherent modelling of involved physical processes.

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F.2. Difficulties to overcome for optimal modelling approach

Approaches usually met in the literature to model urban hydrology belong to four main method types:

- 1. Considering the drainage network only with **1D-modelling** of the pipe flow, the hydrological modelling being based on subcatchment delineation.
- 2. Considering the overland flow only with **2D-modelling**, the sewer system can be assumed unreachable or its volume can be subtracted from the surface flood volume. In this case, runoff discharges may be previously computed and injected on the topography or net rainfall might be directly applied to the surface.
- 3. Considering both sewer system and surface with **1D-1D coupling**, the streets are represented as a network. The hydrological modelling relies on subcatchments or runoff discharge may be previously computed and injected on the topography.
- 4. Considering both sewer system and surface with **1D-2D coupling**. In that case, hydrological modelling can be done under the options of the three previous above-mentioned types.

Types 1 and 2 are approaches that may give interesting first insights, they are however prone to be limited in our case. Indeed, the presence of an urban river and the possibility of pluvial floods lead to the requirement to take into account both overland and pipe flow. Type 3 requires a complete knowledge of surface flow directions to build up the 1D-surface-model, which is not straightforward considering urban furniture and possibly moving flow paths according to rainfall intensity and related runoff depth. Type 4 is remaining to help us to describe the situation, which is partially convenient. Indeed, willing to use the 2D-net-rainfall option, the full extent of the basin, although relatively small, is too important for high-resolution modelling. This type of method thus needs to be adapted to comply with our aim.

F.3. Description of the innovative approach

Preliminary steps consist in delineating the catchment area regarding both topography and sewer network. Indeed, the topographic basin is slightly modified by inflow and outflow pipes crossing its limits. Some areas might be added or removed. A thorough examination is done to estimate the catchment drained area better.

In practice, the limits of the previously determined topographic catchment are displayed overlaying the network layout. Each point where a pipe crosses the catchment limit is recorded and analysed in terms of flow direction, network type and pipe section. The idea is to determine the inflow or the outflow to implement. In the inflow case, the network type might be sanitary, stormwater or combined. The corresponding sanitary flow and/or drained area have to be determined. In case of a strictly sanitary flow, no additional area will be added to the catchment

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surface. Also, the position of the outlet is defined in the network according to the measured data. However, because the interest of the study is to mainly represent the overland flow, the considered surface area will go beyond the catchment limits for the downstream area.

The method consists in splitting the study area into two parts according to the transition point between open-surface and covered river stream: (1) the upstream part characterised by hills and (2) the downstream part where urban flooding is mainly generated by runoff (Figure 66).

The upstream natural open-surface part of the watercourse will be modelled to determine hydrological processes and outflow at the transition point (Transition point in Figure 66). In this way, the computational cost of the hydrological modelling can be significantly reduced. The upstream part of the basin can be modelled as a rural area compared to the downstream part which is quite urbanized.

The downstream part characterized by the underground network will use the output of the first hydrological model as upstream boundary condition. The discharge generated by the upstream overland flow will be driven to the first buried section of the Magnan River. Rainfall data is available at a suitable spatial resolution with rain gauges distributed all along the Magnan River. The idea is to model the urban hydrology in a fully dynamic mode. The estimated net rainfall will be applied to each cell of the topography in order to represent the physical process of runoff generation on the surface of the streets.

The main advantage of this method is the possibility to take benefit of the existing monitoring stations. In fact, there are multiple applications of this modelling system. The objective might be the search for explanations of historical events with simulations of past events. On the other hand, the modelling goal may be to forecast future events, knowing the weather forecast of the next days, to give recommendations to the road management service and to the population. The boundary point between the upstream and downstream parts is chosen so that the upstream module can be replaced by measurements if they are available. This also means that even in the case of historical events, in case of failure of limnimeter station, rainfall data can be used to estimate the discharge at the boundary between upstream and downstream parts. This modular design fully adapts to the local specificities and is prone to be useful for operational applications.



Figure 66. Synthesis of the method detailing modelling goal, computational principal, tool, input, output and limits or added value according to the model area.

F.4. Description of the selected modelling settings

The implemented method uses both model chaining and coupling. These approaches are combined to take maximum benefits from existing tools and data with a possible future use of the modelling system in real-time. The chosen tools for this study belong to the DHI software suite. This set of tools is based on the shallow water equations, also known as Saint-Venant equations. The objective is to integrate advantages of four software and to mitigate limitations of each approach.

In the framework of this study, different choices have been made according to the available data and the objective of the study. The roughness coefficient (Strickler) is first chosen constant over the catchment area with a value of 60m^{1/3}/s. The rainfall is assumed to be spatially homogeneous over the downstream part of the catchment. The area of the buildings is extracted from the DEM and the corresponding amount of precipitation is assumed to fall on the nearby streets. The coupling nodes are the manholes of the network, they are chosen as inlets to simplify the coupling process. However, the inlet ground level is used when available to define the manhole ground level.

Part G Conclusive remarks

Chapter 3 has presented the methodology and the modelling scope which will be applied in Chapter 4 to investigate on urban pluvial flood modelling. Three main steps have been defined to gradually include all necessary aspects to represent rainfall induced processes in urban areas:

- 1. Overland flow with the question of the topography details;
- 2. Underground sewer flow and potential sewer overflow with sewersurface interactions;
- 3. Rainfall distribution between surface and sewer coupled models.

The complexity of the problem leads to a deviation between physical processes and their representativeness. The objective was to determine the potential benefit of such a modelling system including coupling processes while limiting the downside effects of each modelling approaches. Foreseen limitations in the application of this methodology are:

- Currently available network data are limited. New surveys might be necessary.
- Rain gauge data is used. For better rainfall spatial distribution, radar data can be used. The advantage is that the modelling system is ready for that.
- Upstream hydrology processes are simplified using the diffusive wave.
- One transition point is used as chainage point between upstream and downstream parts. Several points might be used to improve the boundary separating both parts.
- The coupling points between the surface and the network models in the downstream part of the catchment can be improved in their description. At the moment, the manholes are used as coupling nodes. However, in the reality, street runoff is driven to stormwater grates which flow to manholes. These grates are located at the sides of the street, whereas manholes are most of the time in the middle of the street. They differ again with their geometry, which may lead to significant variations in the maximum admitted in/outflow. Further developments should include a stormwater grate survey in the 2D domain.

Further research is needed to investigate deeper on coupling parameters used in Mike FLOOD to represent the reality better. For instance, further tests could account for inlet clogging to understand network failure generated by surface issues better. The real layout of the streets is made of inlets which lead to manholes. The hydrological model could also be improved by extracting upstream cross-sections to represent the river better, thus estimating the discharge to the downstream network better in case of forecasting purposes. The existing monitoring system could benefit from this study and could be fully used by determining rainfall thresholds for early warning of the population and adequate crisis management.

Further application of this modelling system could be the addition of water quality module. Pollution loads would be estimated at the outlet of the Magnan and measures could be taken to assess and prevent sea water pollution in the vicinity of the Magnan outlet.

Chapter 4 Modelling applications and result discussions

Part A Introduction

This chapter presents the results obtained from the application of the innovative method which has been presented in Chapter 3. The objective is to model the processes occurring in urban areas in rainy weather and to determine how to improve the use of existing models and tools. Indeed, rather than developing new tools, the challenge this research work aims to address is to understand better thus improve the utilisation of existing modelling tools for stormwater investigations.

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The three main steps of the innovative method are treated successively and applied to the selected study-cases. The St-Augustin district is chosen for the first two steps: (1) Overland flow and topography data, and (2) Pipe and overland flows in interaction. Then the Magnan valley is selected for the third step of the approach: (3) Integrated urban pluvial modelling. Finally, the encountered model instabilities are explained and discussed.



Figure 67. Reminder of the modelling scope of the approach and corresponding applications

Part B Overland flow and topography data

B.1. Study-area



Figure 68. a) Study-case topography and drainage network; b) Flooded street at the point of interest (under St-Augustin Bridge) (From Nice-Matin); c) 3D visualisation of the S4 DEM over the most downstream part of the catchment (red circle indicating St-Augustin Bridge).

The city of Nice is located in the south-east of France and is characterized by its coastal interface with the Mediterranean Sea and high slopes due to the nearby Alps Mountains. The drainage system of the city is characterized by a 510km-long pipe network. A district is selected according to a problematic under a bridge located in a retention area. An area of 3.2km² is drained to a street under the bridge. This location is regularly flooded during rain events (Figure 68b, c). The separated drainage network included in the study area contains 253 stormwater inlets (Figure 68a). The sanitary pipes and manholes are not taken into account.

A high resolution photo-interpreted dataset covering the whole extent of the city has been gathered by the municipality in 2011 (Andres 2012; Morgan Abily et al. 2013). A low altitude flight, a pixel resolution of 0.1m at the ground level, a high level of overlapping among aerial pictures (80%), and the use of an important number of markers for geo-referencing (about 200), lead to a high level of accuracy over the urban area of the city. The average accuracy of the dataset is 0.2m in both vertical and horizontal dimensions. Errors in photo-interpretation

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are estimated to be around 5% after verifications with terrestrial topographic measurements performed by DIGNCA over 10% of the domain covered by the photogrammetric campaign. The selected rain event occurred on the October 3rd 2015 and is characterized by a severe violence in the region with considerable material damages and 21 human losses in cities located nearby Nice. Over the study-area, precipitations have been less important but still of the order of 100-year-return period with a peak intensity of 78 mm/h and an accumulated volume of 74mm within one hour.

B.2. GIS-based results and interpretations

The HR topographic dataset (Andres 2012; Morgan Abily et al. 2013) available for the studycase is analysed with Arc Hydro Tools within ArcGIS (ESRI) regarding drainage lines and contributing areas. The outlet is chosen according to an existing point of interest regularly flooded, a low point located on a street under a bridge near a train-station representing high traffic load (Figure 68).

The first step of the GIS comparison consists in calculating the areas of contribution and longest flow paths for the previously mentioned dataset. This can be done after filling all sinks, calculating flow direction and flow accumulation, stream definition and segmentation, catchment delineation and drainage line processing. Basic pre-processing steps are presented in Figure 69.

The goal of the second step is to identify potential diversion effects of street furniture and buildings on flow paths in the downstream direction. To do that, a set of 20 random points is defined and their flow path to the outlet of the catchment is computed. The calculation is repeated for each DEM and the length of the flow path is compared between the results obtained for each point.

The third aspect of comparison relies on the area drained by each stormwater inlets of the sewer network within the study-area for every DEM. The interest is to detect the changing patterns from the initial DTM to the successive increase of detail level. Furthermore, the total drained area by the set of inlets is calculated and compared for each layer. The interest of this comparison is the observation of the influence of surface features on the connectivity of the surface with the stormwater network, which is a first condition to assess its drainage capacity.



Figure 69. Flow-chart of the DEM pre-processing in ArcGIS (ESRI) (reproduced from (ESRI 2017))

B.2.1. Contributing area and longest flow path

The comparison of the four DEMs gives useful information regarding surface drainage. According to drainage lines calculations, the contributing area varies. Figure 70 shows watershed delineation and longest flow path for each case from S1 to S4. The numerical values are presented in Table 11.



Figure 70. Direct contributing areas and longest flow paths to outlet under St-Augustin Bridge (pointed out by the arrow).

DEM	Direct contributing area (km ²)	Longest flow path (km)
S1	3.24	4.44
S2	3.28	4.51
S3	3.12	4.54
S4	2.73	4.14

Table 11	Results of	f calculations o	f contributing	areas and	longest flow	paths.
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Differences can be observed in the delineation of the contributing area. A major difference occurs for S3 DEM in the South-West part of the study area and for S4 in the North-West part. These results show that, taking for reference S1 (DTM without construction), the presence of buildings (S2) provokes a very slight increase of drained area (by 1%). However, when considering high walls (S3) the drained area is decreased by almost 5%. This means that some walls are diverting drainage lines outside the original catchment boundary. This effect can be observed at a higher magnitude when considering S4, the DEM containing the higher level of details. S4 is characterised by a significantly smaller contributing area, almost 13% less than the contributing area of S3. The evolution of the longest flow path has to be noticed as well. This path is very similar between S1 and S2, while its North part varies. The most noticeable gualitative change can be seen for the south part of the area between S1 to S3 which are similar, and S4, which shows a very different flow path, following another street compared to other layers. Regarding length, S4 shows the most significant difference as well with a longest flow path almost 7% shorter compared to S1. These results demonstrate that the choice of the level of detail will directly influence overland flow modelling. Indeed, as S4 presents a smaller drained area, lower water depths are expected at the outlet of the watershed.

B.2.2. Flow path of selected points to outlet

Figure 71 presents the comparison of the computed values of flow length for a set of 20 random points to the outlet (St-Augustin Bridge) for each case from S1 to S4.

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Figure 71. Comparison of flow length to the outlet for 20 points between S1 to S4 (0 value means no connection to catchment).

In average, the minimum value is increased by 21% within a range going from 0 up to 87%. These gaps may influence overland flow significantly. Flood kinetics is thus depending on street furniture included in the DEM. According to the graph, there is no general trend regarding which layer gives a longer flow path. S4 shows the minimum value for six points and the maximum for seven other points out of 20. Six points have their minimum value with S1 layer. For further comparison, a higher number of points should be selected.

B.2.3. Area drained by stormwater inlets

The drainage area of each of the 253 stormwater inlets is computed individually and summed to obtain a total drained area for each DEM S1-4. Several comparisons are presented in Table 12.

DEM	Total drained area (km²)	Difference to S1 (%)	Difference to S2 (%)	Difference to S3 (%)
S1	3.94	+ 0.0	/	1
S2	4.49	+ 14.0	+ 0.0	1
S3	4.48	+ 13.9	- 0.12	+ 0.0
S4	4.22	+ 7.22	- 5.96	-5.84

Table 12. Comparison of the total drained area to stormwater inlets.

The differences to S1 situation show that the drained area is highly increased with buildings by 14%. The difference between S2 and S3 is not significant (-0.12%). However, the fourth and fifth columns show that the consideration of all urban features (S4) reduces the drained area by almost 6% compared to the presence of buildings (S2) and the presence of buildings

and high walls (S3). This means that using S4 catchment delineation, lower volumes would be drained to the sewer system in the 1D-modelling step.

B.2.4. Comparison of accumulation points and stormwater

inlets location

Another way to look at the surface aspect of stormwater drainage is to consider the concordance or the gaps existing between the location of accumulation points of the topography called "drainage points", and the position of stormwater inlets. Figure 72 shows this comparison for the downstream part of the St-Augustin district.



Superimposition of surface and underground drainage axes

Figure 72. Drainage points and stormwater inlets (downstream part of the St-Augustin District)

The area of interest is circled and the number of drainage points is clearly higher than the number of stormwater inlets for the same location. This constitutes part of the explanation of the frequency of floods recorded at this location.

B.1. Modelling approach

1D and 2D models are here run separately. The 1D model of the sewer system of the whole city is based on the approximation of the SWEs (Shallow Water Equations) system solution using Mike URBAN (DHI). The model is provided by Nice Municipality and described in (M. Abily, Scarceriaux, and Duluc 2015). The rainfall event of October 3rd 2015 has been simulated using a spatially uniform rainfall data recorded every two minutes. The interest to use this model is double: *(i)* the results can be used as a reference and it allows to check the effects of introducing in the model different sizes of contributing areas depending on the GIS analysis; *(ii)* the types of interaction between the sewer system and the surface can be identified by simulating in 1D the rainfall event, which is useful for the upcoming coupling with 2D surface flow model.

The overland flow resulting from the selected intense rainfall event is modelled using the 2D SWEs based code FullSWOF_2D. The aim is to compare the effects of the level of topography detail included in the model on overland flow properties (water level and hydrodynamic) in order to figure out the appropriate level of detail to integrate in the modelling approach. To achieve this goal, the HR (1m) DEMs S1 to S4 were used as computational grids for the simulation. The size of these grids is larger than the sub-catchment area (3.3km²) with 5.9 million of computation points. A variable time step is used for the temporal discretization based on the CFL criterion (fixed to 0.45). Computations were run using the MPI parallel version of the code over 64 CPU and required 24 hours to simulate the 5-hour-event (including the 2-hour-rainfall peak which generated flooding issues). Net rainfall is introduced as spatially homogenous without considering infiltration. However, it should be mentioned that the SWEs are not solved over the buildings footprint. The roughness coefficient is set to a spatially uniform value of 0.06 s.m^{-1/3}. Access to the sewer system is considered as non-available and the boundary conditions are closed.

B.2. Discussions and perspectives on hydrodynamic modelling

The existing validated 1D-model of the sewer network of the whole city created with Mike URBAN software (DHI) is run for the October 3rd rainfall event. Six nodes where the sewer system is contributing to the surface flow are detected in the study area. They are located in the downstream part of the catchment, in a rather steep sub-area which is contributing to the point of interest for both surface and underground flow. Future work regarding 1D-sewer system modelling aims to perform a sensitivity analysis using S1-S4 new detailed sub-catchments delineation to define manhole contributing areas. Purpose will be to study impacts of these sub-catchment delineation variations on the sewer drainage modelling. Moreover, considering future coupling with 2D models, the interactions between sewer and surface model drainage (*e.g.* nodes identified as contributing to surface flow) might be different and require further thorough analysis.

Second step for future improvement will use results of the 2D surface runoff modelling. 2Dresults presented in Figure 73 are in a realistic order of magnitude according to the observations under the bridge. Four models using S1 to S4 were run. Figure 73 illustrates results of the 3rd of October flood event modelled using HR DEM (S3). As expected, it shows that the magnitude and kinetic of the water depth evolution is impacted by the HR level of topography (Figure 74a). Moreover, an illustration of the impact of the detail of the topography on overland runoff flow path confirms that a street can be flooded or not (Figure 74b red dotted line and black arrow) depending on included street features on the surface model. A deeper analysis on the required optimal level of detail will be performed focusing on water levels over manholes location when using 2D surface modelling to understand and quantify better effects of the HR topography on 1D-2D coupling between drainage models. Moreover, these tests with FullSWOF_2D code are a first step in the process of analysing HR topography details impact. Indeed, for the objective of operational tool for stormwater management, to optimize computation time, other codes (*e.g.* DHI's Mike 21) will be tested and compared.



Figure 73. Overview of the simulated water depth of the flood event at 10:30 pm using DEM S3 at the southern part of the catchment



Figure 74. a) Water depth evolution at St-Augustin Bridge with S1-4; b) Simulated water depth of the flood event at 10:30 pm comparing DEMs S2 and S3 at a northern part of the catchment.

The level of detail in the DEM impacts surface flow paths, thus diverts overland flow direction and necessarily changes downstream water elevations. Therefore, the consideration of the level of details and the selection of the most suitable one impact the modelling results.

B.3. First step conclusion and prospects

This part has presented preliminary results given by a method set in order to improve operational modelling of urban systems regarding flood kinetics throughout detailed urban topography. Results showed that a thorough analysis is required to select the best conceptualisation of the topography representation in models. Indeed, the selection of the level of topography details to include impacts the results to a great extent. This statement is confirmed to be valid for both buried drainage system (by impacting collecting areas definition) and surface drainage modelling. The higher level of details is not necessarily the best choice to model urban flood in a realistic way. Moreover, in this modelling approaches (GIS and Hydrodynamic modelling) surface features are included in the topography and therefore hundred percent impermeable which is not a fully satisfying statement.

Furthermore, effects not encompassed here such as clogging effects, surface features which temporally evolve quickly over urban area or which can be destroyed by flood event, *etc.* are sources of uncertainty affecting drainage path. However, it is promising to achieve an analysis of the optimal feeding that this emerging type of dataset can provide to operational 1D-2D modelling for stormwater management.

Finally, it is interesting to mention that this study not only confirms the important impact of the level of details of topography on both surface and sewer drainage systems, but presents a methodology to qualify and quantify these effects. The presented study-case and methodology opens the door to tackle this problematic. The reach of this study allows to continue working on improving assessment of an effective operational 1D-2D coupling.

Pipe and overland flows in Part C interaction

C.1. An evolving district prone to pluvial floods

The district of Saint-Augustin is taken once again as a study-case to examine in detail the interactions between the sewer pipe flow and the overland flow. The main downstream street is selected as it leads to the main point of interest, the street-section located underneath the railway bridge.

Two historical rainfall events are selected to be modelled, on October 3rd 2015 and September 9th 2017, given their important consequences in this area. The second reason of their selection is the availability of pictures (Figure 77 and Figure 78) of the surface consequences, which is rare in such analyses.

Table 13.	Details	of the	selected	rainfall	events
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Event	Total precipitation	Maximum intensity (mm/h)
	(mm in 2h duration)	
October 3 rd 2015	73.4	78
September 9 th 2017	50	116



Figure 75. Hyetograph of the October 3rd 2015 event (PLNIC20, NCA Metropolis)

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Figure 76. Hyetograph of the September 9th 2017 event (PLNIC20, NCA Metropolis)

The rainfall data is taken from the nearby rain gauge "PLNIC20", given the limited area of this urban catchment.



Figure 77. Picture of the bridge of interest (in the background) after the 3rd October 2015 event

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Figure 78. Picture of the bridge of interest on the 9th September 2017 event

The underground sewer network is modelled with Mike URBAN (DHI 2014c). The existing model of the whole city is used to take into account both stormwater and sanitary water. This global model of the Haliotis basin includes 850 catchments and 320 km of sewer network. The method of the linear reservoir is used to perform hydrology computations. This model is fully described in Chapter 2.

The surface topography is represented by the selected most suitable data from the previous part analysis. The previously defined S3 DEM features buildings and main high walls as urban furniture. Indeed, it was previously explained that S3 is a satisfying compromise between urban furniture accuracy and overland flow path reality. As this level of detail has been previously determined as most suitable, it is now used to build a 1m-resolution-2D surface model for the coupled modelling system. The location of the catchment and its DEM are displayed in Figure 79.

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Figure 79. Situation of the downstream part of the Saint-Augustin district, the location of the bridge is circled

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Rainfall Coupling with D sewer system model (Mike URBAN) Mike FLOOD 2D overland model (Mike 21)

In this step of the approach, rainfall is only applied to the 1D model as explained in Figure 80.

Figure 80. Modelling approach

A number of 113 nodes are selected to be coupled between the surface and the sewer model. Their position is strategically chosen all around the area of interest, the St-Augustin Bridge, as presented in Figure 81. The coupling parameters are the following:

- Maximum flow of 0.1 m³/s
- Inlet area of 0.16 m²
- Orifice equation method
- Discharge of 0.98%
- QdH factor of 0.05.

In the Mike 21 surface model, the 1m-resolution structured grid covers an area of 3.8 km². The flooding and drying depth are selected as 0.012m and 0.008 m respectively.

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Figure 81. Visualisation of the coupling interface in Mike FLOOD (DHI) and location of the coupled nodes

The results of both events will be presented and linked to the existing measurements in the network and pictures on the surface. Limitations of the present analysis will be focused on and explained.

C.2. Modelling results

C.2.1. The October 3rd 2015 event

Figure 82 shows the flood extent generated by the sewer overflow during the October 3rd 2015 event at the moment of the peak.



Situation of the downstream part of Saint-Augustin district

Figure 82. Flood map of the October 3rd 2015 event in St-Augustin district downstream part

The simulation gave water level results of values near 1 m and higher in the area seen in Figure 77. This is possibly what happened, explaining how the car on the picture has been raised on the parking bollard.

C.2.2. The September 9th 2017 event

Figure 83 shows the maximum flood extent generated by the sewer overflow in the downstream part of the catchment.



Figure 83. Flood map in the Saint-Augustin district

The modelling results show a water elevation of 50 cm at the location of Figure 78 which is in the order of magnitude of the water accumulation seen on the picture.

C.3. Discussion and limits

The results of this part are presented in terms of flood extents and are in concordance with the available pictures of the surface consequences of each selected rainfall event. However, some limitations should be discussed.

The topography data has changed due to big extent construction works for the new tramway line. This is a limit of the model especially for the most recent event which took place in 2017 whereas the topography data were collected in 2010-2011.

Not all the overland flow processes are taken into account at this stage. For example, during the October 3rd October event, it is clear that flooding was mostly generated by overland flow. In the Mediterranean context, intense event with short durations generate important volumes of overland flow which accumulates on the surface before being drained to the sewer network. This means that the main limit of the approach presented in this part is the wrong representation of the flood dynamics of such urban sudden pluvial floods. Part D comes next and presents the extension of this coupling method to the next level with an integrated approach.

Part D Integrated urban pluvial modelling

D.1. The Magnan catchment: a typical complex suburban valley in the French Riviera

The Magnan basin is located in the western part of Nice city, France. This catchment drains an area of 17km² and can be divided from upstream to downstream into two main parts regarding the changing geometry and features of the river configuration. (1) The river stream is first natural and hilly in the upstream part with a steep average slope of 5.5 % and then flows to an artificial riverbed along the first urbanized areas. A road has been built along the watercourse being at risk in case of flooding. (2) In the denser urban area, the proportion of buildings is three times more important. The river stream enters a piped underground section as far as its outlet to the Mediterranean Sea with a downstream slope of about 1.5 % (Figure 84). The infiltration rate is assumed to be low in the upstream part of the catchment due to the steep slopes.

Historical facts and a study of the river dynamic can be found in two engineering reports (Groupement SAFEGE 2003) and (Hydratec and Asconit 2012). Seven historical flood events have been recorded since 1787. Most recent events are recorded in October 1999 and November 2000 but no reliable discharge data is available and occurrence of landslides has been mentioned. The order of magnitude of the response time of the catchment is between 15 and 30 minutes. This quick hydrological response can lead to flash floods in the downstream part of the catchment in case of heavy rainfall. However, few flood events have been recorded because of the rather high flood perception threshold of the riverside inhabitants. A testimony has been recorded at the location of a walkway crossing the river right upstream the beginning of the downstream part of the Magnan basin previously described. The witness living there kept the memory of a flood event when this walkway was flooded. According to the cross-section at this location, the discharge is estimated to be about 30 m³/s to flood the walkway, which corresponds to a specific discharge of 2.5 m³/s/km² (for a drained area of 12 km² at this location). Lastly, beside the flooding rise, it has to be stressed that in the summer season and under dry weather, the Magnan flow is diverted to the sewer system to protect the water quality of the nearby beaches.

This specific configuration of the suburban basin leads to the need for an integrated modelling system which includes hydrology with rainfall-runoff modelling, hydraulics with runoff routing along the surface flow paths, absorption to the sewer system through inlets and stormwater curbs and interactions between surface and sewer.

D.2. Existing data and specificities

Several datasets are available regarding topography, drainage network, rainfall and hydraulic measurements. Most of them belong to the municipality Métropole Nice Côte d'Azur (MNCA) and are relatively young with the oldest rainfall datasets dated from 2005.

An H-R photo-interpreted dataset together with a 0.5-meter-resolution DEM covering the whole extent of the city have been gathered by the municipality in 2010-2011. This dataset has an average accuracy in both planimetry and altimetry of 0.2 m. Datasets is constituted of more than 50 classes, including thin features such as walls, roundabout, sidewalk, *etc.* and is fully described (Andres 2012; Morgan Abily et al. 2013). This data is used to build a DEM to represent the topography of the catchment. The selected urban furniture to include belongs to 12 classes and goes to the level of detail of fine walls which influence flow path as described in (L. Salvan, Abily, and Gourbesville 2016).

A Flood Warning System has been set-up since the end of 2013 including two rainfall stations and two ultrasonic limnimetric stations which record water depth and calculate discharge every six minutes in the upstream part of the catchment and at the transition point between the freesurface and piped river. At the present time, this warning system is not fully used and warning thresholds have been roughly estimated. Another set of four rain gauges records rainfall in the Magnan basin and the stations are located all along the river stream.

Regularly updated but partially detailed network data are available within the whole municipality extend. The dataset used in the framework of this study was updated in 2015. A pre-existing 1D-model is also used as a reference and as secondary source of information regarding network data. The combined length of conduits in the Magnan basin is approximately 23 km which can be evenly divided between stormwater and sanitary flow. The channelized Magnan River is included in this value. In the downstream separated sewer network, four ultrasonic sensors are available: two for the stormwater (*e.g.* the Magnan River) and two others for the sanitary flow. The main limit of the hydraulic data is the calculation of the discharge from the measurements which would need an in-depth review to update the calculation rules. More sensors could also be implemented along the watercourse at strategic locations such as tributary junctions.



Figure 84. Overview of the Magnan Basin characteristics including from upstream to downstream the evolution of the river bed and the existing measure stations and sewer network.

In the same as previously in St-Augustin District, the downstream part of the Magnan Basin is zoomed in and the focus is on the location of drainage points, where overland flow accumulates, and the position of stormwater inlets, where overland flow is prone to be driven to the underground drainage system.



Superimposition of surface and underground drainage axes

Figure 85. Drainage points and stormwater inlets in the Magnan Valley downstream part

The number of stormwater inlets seen in the downstream part of the Magnan Valley seems overall sufficient and close enough to drainage points locations. However, in the circled position no inlets can be seen from the map. However, after verification on the field, several stormwater inlets exist at that location but were not identified.

D.3. Modelling application and results

The application case of the Magnan Valley is the occasion to test the innovative concept of the method proposed here. Indeed, two simulations are used to investigate on the impact of the rainfall distribution over a 1D-2D coupled model. The Magnan Valley is divided into 21 subcatchments. The downstream subcatchment is selected to be the core of the experiment due to its dense urbanisation and its proximity to the "Promenade des Anglais". Moreover, a fire station is located at its Eastern limit. This strategic position for rescue operation was flooded during the October 3rd 2015 event. The global modelling system is presented in Figure 86.



Figure 86. Magnan Valley modelling system: subcatchment delineation and location of the downstream subcatchment selected for comparison of Cases 1 and 2

D.3.1. Modelling principles

(a)Sewer model

The 1D sewer model is built from a conjunction of two data sources. Indeed, the existing global model could not be used directly because of the catchment delineation which does not fit the delineation made from the newest topography data. It is important to have the same catchment

Figure 87. 1D stormwater network model of the Magnan Basin

delineation between the surface and the sewer models to avoid precipitation distribution mistakes. Also, the global model dates from 2014 and new sewer data have been collected since then. For these reasons, a new hydrodynamic model of the Magnan Valley was built in Mike URBAN, from the new sewer system data and the existing global model. Moreover, because the drainage system is mostly separated in the Magnan Valley, the decision was made to remove the sanitary network from the analysis to focus on the stormwater network. In this way, the delineated catchments are only hydrological catchment, with the purpose to represent rainfallrunoff transformation.

The step of the construction of the network from the two available sources of data was essential but time-consuming. Actually, network data are sparse and some characteristics are missing. To be able to build the model, several assumptions were made. For example, when dimensions like manhole diameters were missing, the average of all manholes diameter was defined. Moreover, special care was taken to consider network sections located at the catchment boundaries. Each crossing pipe was examined as well as the slope direction and the upstream and downstream elements. When significant area (greater than 0.1 km²) was found to be drained to the central network of the Magnan Valley, it was added to the global catchment area. However, upstream sections of the network belonging to nearby villages were removed from the model. Also, the data was checked carefully and corrected when needed. For example, the geographical reference of some objects was sometimes wrong, which resulted in disconnected manholes

and networks. Finally, the stormwater network was selected and the sanitary sections removed. The hydraulic structures and parameters were taken from the existing global model, as well as the upstream natural sections of the Magnan River. Available limnimetric data was used to calibrate the model which uses the linear reservoir hydrological module of Mike URBAN (DHI 2014d).

(b)Surface model

The surface model of the 0.21km²-downstream subcatchment of the Magnan Valley is built within Mike 21 (DHI 2016a). Because long computation durations occurred in the simulations performed in Part C, the topography data was resampled to a 2meter-resolution. Also, the footprint of the buildings was simplified and extruded at an elevation of 50 meters from the DEM elevation. The land value is defined at 50 meters, in this way the net rainfall is not applied on the buildings footprint. The precipitation quantity falling on the roofs is assumed to be drained to the streets. To model it, the percentage of buildings' footprint surface in the catchment calculated (27%) and is the corresponding amount of precipitation is added to the net rainfall at each rainfall data timestep. The boundaries are closed.



Figure 88. 2m-resolution raster used for the surface model of the downstream catchment

The 2D parameters were defined as follows: flooding and drying depth are set to 0.003 and 0.002 meters respectively.



(c) 1D-2D coupled model

The 1D sewer system model and the 2D surface model are coupled with Mike FLOOD (DHI 2016c). A total of 31 nodes are coupled between the 1D and the 2D models. One surface cell with an area of 2 m² is coupled to each 1D node. The selected coupling parameters are:

- Maximum flow of 0.1 m3/s
- Inlet area of 0.16 m2
- Orifice equation method
- Discharge of 0.98%
- QdH factor of 0.05

The location of the coupled nodes on the 2mresolution grid is displayed in Figure 89.

Figure 89. Location of the 31 coupled nodes (red squares)

(d)Modelling cases

Two simulation cases are defined to highlight the interest of the method. These cases are presented in Table 14. To complete the comparison, a reference case for the surface aspects is defined as Case 0.





The January 4th 2014 event is selected in this part as it was an average event with enough rainfall to generate interactions but no extreme quantities of precipitation.



Figure 90. Selected event

This event is chosen because of its one-day-duration and its two sub-events separated by approximately five hours. This is favourable to examine several surface-sewer interactions.

MODELLING APPLICATIONS AND RESULT DISCUSSIONS

D.3.2. Case 1: rainfall applied to the 1D model only

In Case 1, rainfall is only applied to the 1D model as explained in Figure 91.



Figure 91. Modelling approach of Case 1

In this case, only the flooding generated by the sewer overflow will be simulated. This technique is currently applied widely in engineering consultancies.

D.3.3. Case 2: rainfall applied to the 1D model (upstream) and

the 2D model (downstream)

In Case 2, the integrated method is applied and the rainfall is distributed between the surface and the sewer as explained in Figure 92.



MODELLING APPLICATIONS AND RESULT DISCUSSIONS

Comparison of modelling cases D.3.4.

The simulations of Cases 0, 1 and 2 are compared according to two surface aspects:

- Flood extent in the downstream catchment; _
- _ Water level near fire station;

Then, the simulations of Cases 1 and 2 are compared according to two underground aspects:

- Outflow of the subcatchment and of the Magnan Basin;
- Exchange flow at coupled nodes.

(a)Surface aspects

The flood maps of Figure 93, Figure 94 and Figure 95 are produced at 20:49 on January 4th 2014.



Situation of the downstream part of Magnan Valley

Figure 93. Case 0 flood extent

In Case 0, water elevations around 40 cm are simulated near the fire station.



Figure 94. Case 1 flood extent

A very limited area of the catchment is flooded in Case 1, located in the downstream part. There is no flood and no water accumulation near the fire station.



Figure 95. Case 2 flood extent

In Case 2, water elevations in the order of 3 cm are simulated near the fire station.

The three flood maps show the same area of maximum elevation, located at the South-Western boundary of the model domain. This is the natural drainage area of the catchment. Greater differences in water elevation can be seen in Figure 94 where Case 1 is displayed. Indeed, no rainfall is applied at the surface.

Figure 96 shows the difference between the ascii files produced for Case 2 and Case 0.



Situation of the downstream part of Magnan Valley

Figure 96. Difference between flood extent of Cases 0 and 2

Only little differences can be observed between Cases 0 and 2, in the order of magnitude of the millimetre or centimetre. Green colours show areas where the water elevation is higher in Case 0 than is Case 2. This is the situation in the greater accumulation area where the drainage network plays its role of decreasing the water level at the street surface.



Figure 97. Situation of the selected catchment of interest and comparison elements

There are five interacting nodes (circled in Figure 97) in Case 1 with in total 42 m^3 of sewer overflow and 3773 m^3 of drained volume from the surface to the sewer. In Case 2, a total of 347 m^3 are drained from the surface to the sewer via the 31 coupled nodes. There is no sewer overflow during the event.

Links A and B are selected to examine the discharge at two locations: (A) outflow of the downstream catchment, and (B) outflow at one of the Magnan's outlet.

Node N is selected to look at the exchange flows between the surface and the sewer.

The pipe flow is first compared for two locations in the network (bold blue pipes in Figure 97) for the whole duration of the simulated event.

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Figure 98. Discharge of Cases 1 and 2 at Link A

Link A discharge shows important differences between Cases 1 and 2, with a low flow in Case 2. However, when zooming (Figure 99) at the scale of this low flow, variations appear, following the variations of the rainfall event in the same way as the discharge in Case 1.



Figure 99. Zoom on Link A discharge of Case 2

The first comparison in the graph presented in Figure 98 shows the important gap between Cases 1 and 2 in terms of pipe flow. Therefore, there is a very small stormwater volume drained to sewer from the surface, which was previously highlighted with the difference of exchanged volume.



Figure 100. Discharge of Cases 1 and 2 at Link B

Figure 100 shows the discharge at the outlet of the Magnan, which is poorly affected by the difference between Cases 1 and 2.

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Figure 101. Flow exchange between Mike URBAN and Mike 21 for Cases 1 and 2 at Node N

This graph presents flow exchanges between sewer and surface (positive discharges), and surface to sewer (negative discharges). Again, the results show that there is no sewer overflow in Case 2.

Table 15 gives an overview of the results presented for the integrated pluvial flood modelling.

Table 15	Summary	of the	results	obtained	for	Cases	0,	1	and	2
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Simulation cases	Surface	aspects	Coupling and Underground aspects				
	Flood extent	Maximum water elevation near fire station (cm)	Exchange flow	Subcatchment outflow			
Case 0	Wide extent	~ 40	-	-			
Case 1	Limited extent	-	5 nodes, 2 directions	Q _{peak} > 0.2 m ³ /s			
Case 2	Wide extent	~ 3	31 nodes, no sewer overflow	$Q_{peak} = 0.005$ m ³ /s			

It should be stressed that in this modelling system, two different catchment outlets are defined, one for the underground network (the Magnan outlet on the beach), and one for the surface catchment (located at the South-Eastern boundary).

D.4. Synthesis of the integrated approach

The innovation presented in this part consists in applying net rainfall inputs on the surface grid to tend to a modelling approach closer to the reality of the physical processes. Instead of using a lumped linear reservoir method, the idea is to apply rainfall on the mesh cell and represent the first moments of a rainfall event as it happens in reality, by accumulating step-by-step and by following the overland flow paths prior to be drained to the underground sewer system. To comply with computational costs of such approach, this has been done by distributing rainfall inputs between both surface, for a defined area of interest, and lumped network model, for the upstream parts of the model.

The integrated approach proposed here features several limits for which a solution should be found to bring this approach to the operational level:

- The computational cost is relatively high.
- This modelling system is source of additional model instabilities.
- Limited volumes are drained to the sewer network.

Several perspectives are identified as potential directions for further developments with this approach, among which:

- Part of the geometrical data of the network is missing and was assumed to build the model. A wide campaign could be held to check measurements and fill missing data, especially regarding manholes and pipes diameters.
- Cross-sections could be extracted from the latest topography data available to update and improve the upstream natural section of the Magnan River.
- Rain gauge data was used in this application but further developments could be done to integrate the utilisation of radar rainfall data.
- The upstream hydrological processes could be further investigated with other approaches. Mike SHE (DHI 2016d) could be used to test the diffusive wave method in the suburban case.

Part E Conclusive remarks

Chapter 4 has presented three modelling applications which were implemented in three steps of an overall methodology. The basic principle of this innovative approach is to examine physical processes in the reality and to determine a way to build a model as close as possible to this reality. This point of view is motivated by the specific issues encountered in Mediterranean cities in rainfall conditions. Currently, populations are still poorly educated to react in case of a sudden urban flood. Unfortunately, 21 casualties were caused by the October 3rd 2015 event. This is why modelling should be developed to understand such events better and forecast damages and vulnerable areas as much as possible.

To move in this direction, three main modelling steps have been defined:

- 1. Overland flow and topography data;
- 2. Pipe and overland flows in interaction;
- 3. Integrated urban pluvial modelling.

These three aspects have led to different results which can be summarised as:

- a) Topography data is essential in flow path definition and significantly impacts hydraulic modelling results.
- b) Sewer overflow is one aspect of urban flood issues but represents only part of flood sources. Overland flow generated by runoff should be included in flood models.
- c) Integrated urban pluvial modelling is possible with existing tools and can represent the reality better.

As said previously, modelling tools have numerous limitations and modelling results represent high-quality insights only when the feeding data are of high-quality. Moreover, input data should be in line with each other. For example, modelling results would suffer from poorly updated sewer network data even though the topography data is of very high quality and high resolution. On top of that, it should be kept in mind that each good modeller should have an accurate knowledge of the study-case situation and goes on the field to make sure no important information related to the problematic has been missed. Also, an accurate knowledge of the institutional context is required, for example being aware of the different companies operating in the area. In the context of stormwater management, the modeller should be aware of the sewer system operators, stormwater operators (which are not always the same persons), the wastewater treatment plant and reservoirs company, as well as information seeming trivial but are not, like the way that streets are cleaned and where surface waste goes. Modelling of the rainfall processes is only one of the available tools and techniques to tackle our issues. Sets of different actions are practicable and can be planned in parallel.

Chapter 5 comes next with practical aspects of stormwater management which cannot be disconnected from the previously presented modelling results. The success of any modelling approach is linked with the ability of the modeller to adapt to the institutional context and local background specificities.

Chapter 5 Practical recommendations to city operators and managers

Part A Introduction

This chapter focuses on the practical needs and implications of city operators and managers. The eventual objective is to contribute to shape an efficient and valuable link between the research world and the operational field. Where concepts and applications meet, there should be no room for misunderstanding or tools misuse. This thesis is not the first attempt in this approach but collects a wide range of information and aspects enabling to draw a synthetic picture of the state of knowledge at the writing date.

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As modelling tools and approaches have been developing widely, an important aspect is to understand the implications of a model better and to remember the limits and application framework. Too often in practice very little room, time or money is left to ensure the necessary engineering explanation of these elements to the final user. Eventually, information might be lost and modelling results might be misused.

Also, a great issue consists in choosing between the trend of the very detailed models in the tendency of high-resolution data and modelling and the simpler and faster tools. We will see throughout this chapter in which way these two trends may be used in stormwater management depending on the current phase related to the crisis temporality. The latter can be represented as a continuous cycle of three periods of variable duration (Figure 102). The cycle starts at normal operation mode with the exploration of prevention and protection measures. Eventually, a crisis occurs, the operation is reduced or stopped and the selected protection measures get the chance to show their abilities through a real-life test. When the crisis is finished, the demanding period of recovery begins to go back to the normal operation mode.



Figure 102. Phases of crisis management

The three objectives of flood management in urban areas are the following:

- 1. Population protection
- 2. Damage cost reduction
- 3. Quick recovery

When dealing with city management regarding stormwater, the institution in charge may face several difficulties, the main one being the diversity of aspects related to this topic. First of all, stormwater presence and quantity depends on the local climatic conditions. This means that there is an unlimited range of diverse conditions which can occur. In the same way, the spatial distribution of a rainfall events is a step forward making each event a unique case. The consequences of each event may thus vary significantly. Second, when drained to the sewer system, stormwater may, or may not, be mixed with sanitary flow. According to local drainage system, stormwater may, or may not, be treated before being discharged to the natural

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receiving water. Therefore, the analysis of stormwater quality aspects and development of environment protection measures is becoming crucial to reduce the threats to life quality.

These two main consequences of rainfall over urban areas are linked with its quantity and its quality. However, flooding, soil erosion and water pollution cannot be considered together at all moments of the management process. Priorities will emerge to the managers especially in case of a crisis.



Figure 103. The four aspects of stormwater management

Part B Review of stormwater management practices

This paragraph presents a brief review of key elements of stormwater management up to now. A first step consists in using planning tools to draw a precise description of the territory particularities. When necessary information is compiled, adaptation measures can be planned. Stormwater management measures can be divided into three main types: hydraulic structures, surface mitigation measures and real-time control of drainage system. Through the different references, local public policies will emerge depending on the location and the context.

B.1. Hazard mapping methods

The idea behind stormwater management concept starts with flood risk mapping. Using all available data on the studied territory, the objective is to map the consequences of an historical or a designed event over the selected area to highlight the zones at risk and where mitigation measures might be set-up. In other words, runoff mapping should enable to summarize the runoff processes, their location and consequences in the city. This is the first tool to use to warn population but also to prepare any further analysis or modelling work.

Several kinds of floods can be encountered, which means that several types of flood risk maps are expected over the same area. Flood maps can first be produced to display the flooded areas while a river floods the city or in case of sea submersion. But this paragraph focuses on different ways to map the consequences of runoff over a city. In all cases, a map can be produced from two main origins: (1) simple topography analysis and (2) simulation results.

In France, there is no national compulsory neither recommended method to produce a map of runoff generated from rainfall (CEPRI 2014). Several institutions are developing their own local methods in parallel with the already existing fluvial flood maps. This means that flood maps are mostly incomplete as they do not represent pluvial flooding. However when existing, runoff maps follow the same trend in representing main surface flow paths and accumulation areas. What mostly differs is the modelling method chosen to produce the necessary information in terms of water depth and velocity to generate the map.

An example is presented in the city of Lyon (Sibeud and Koch 2016). This paper presents the main principles of runoff mapping and a new approach developed to improve the basic mapping. In this approach, the metropolis territory is modelled with a 2D free-surface flow model using flexible triangular mesh. The land uses, land furniture and hydraulic structures are represented with a range of roughness coefficients. The principle of a runoff mapping is to display the following elements (Figure 104):

- The production areas:
- The axes of transmission, concentration and acceleration;
- The areas of accumulation. •

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Figure 104. Illustration of the three main elements of runoff processes

Another method has been developed to help figuring out runoff hazard on railways (Lagadec et al. 2016).

In other points of view, risks related to flooded streets can be defined by examining the hydraulic parameters of street flow with the concept of risk criteria for pedestrian in mind (Martínez-Gomariz, Gómez, and Russo 2016). Real-scale experiments have been carried out with persons crossing a flooded street in different conditions of flow depth and velocity. The product of these two variables is the main conventional criteria for pedestrian stability. The experimental results were confronted to the related state of knowledge and it was found that a threshold of 0.22 m²s-1 describes the lower instability function (Martínez-Gomariz, Gómez, and Russo 2016). The authors of this article propose to use their findings to improve stormwater drainage design. However, this pedestrian stability criteria could be used to map the hazard levels for pedestrians (and extended to vehicles) in flooded streets for typical rainfall events modelled with either 1D street network model or 2D overland flow model. Modelling results could be used as indicative maps for rescue services to help improve evacuation efficiency.

B.2. Adaptation methods

In case of a heavy rainfall, high amount of runoff might be produced. As very often in such cases runoff volume exceeds drainage network volume, an alternative measure would be to store more volume where needed and wait for the recovery of the network capacity to allow stored volumes to access the piped network.

Several methods have been developed to store stormwater of combined water. These methods can be divided into two main types: the hydraulic structures and the stormwater mitigation facilities. Other adaptation methods consist in improving the management of the sewer network without transforming its structure, or only by adding few devices. Real-time control (RTC) of sewer systems is a developing trend for sewer systems operators willing to reduce construction costs or when no surface space for mitigation measures is available.

Modelling tools and techniques are now widely available and developing worldwide. Modelling tools may be used for several approaches of urban hydrology issues. The first approach consists in building a model to understand better the way physical processes work, a "model of understanding". The second approach would focus on the modelling of future construction projects to define their consequences on local stormwater management. The third approach consists in using the previous model of new urban design to check the implications for downstream areas.

B.2.1. Stormwater storage in the underground drainage

network

Storage might be used in sewer systems for two purposes: (1) to reduce flood volumes in the streets; (2) to retain parts of polluted stormwater volumes to protect receiving waters (Butler and Davies 2010). Storage tanks might be online or off-line. On-line storage tanks are built in series with sewer pipes. Typical on-line storage can be oversized sewers. Off-line reservoirs are designed in parallel with the sewer system. In general, overflow and throttling devices are more complicated in the case of off-line tanks, while they require less volume than on-line tanks for similar performance (Butler and Davies 2010).

In the case of Nice, both storage tanks are off-line and can be disconnected from the drainage system when necessary. But wide storage stormwater sewers exist, like for example in the case of the Magnan aqueduct, and all aqueducts in Nice.

An example of new storage basins planning is presented for the Spanish sea resort at Playa de Gandìa located 65 km South from the city of Valencia (Tomicic, Mark, and Kronborg 1999). The situation is a flat urbanised stripe along the beach with high difference of population in winter and summer seasons. An urban flooding alleviation study has been carried out by DHI to identify and plan an adequate solution to address the serious flooding and excessive combined sewer overflow issues. The hydrological and hydraulic modelling system is developed using MOUSE (ancient version of Mike URBAN) after a deep GIS analysis was conducted. A dual drainage model is designed with two 1D-layers: one for the sewer network,

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the other one for the streets network. Finally, the proposed solution includes the construction of six storage basins and the implementation of new pumping stations.

The major drawbacks of the implementation of storage tanks are the important cost of the construction works and the relatively important space needed to build them. Depending on the considered area, space would not necessarily be an issue. However, regarding the French Riviera and its already fully built-up coasts (which are the vulnerable areas), available space is definitely the main issue.

Other storage solutions have been developed to optimise the use of the storage capacity of the whole drainage system. Small devices can be distributed over the network especially in upstream and wide sections. A new kind of valve has been designed by the start-up company F-REG (f-reg.fr) specifically for this purpose. The interest is to implement low-cost devices at chosen location according to the accessibility and the upstream storage potential. A leakage rate is set and hydraulic cylinders are designed to let the gate closed until a certain hydraulic head when the pressure is high enough to open the gate.

B.2.2. Urban stormwater management by alternative techniques (SUDS, LIDs, BMPs and Co)

Other types of stormwater storage facilities have emerged for the last decades. Situated at the opposite engineering point of view. Instead of the conventional pipe engineering solutions, the idea is to use more surface natural means to drain stormwater and to reduce runoff volumes, especially by reducing runoff transport to the downstream areas very quickly like piped systems do (Butler and Davies 2010). Many different types of SUDS have been developed among which we can cite:

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Green Roofs are another variation of a bio-retention cell that have a soil layer laying atop a special drainage mat material that conveys excess percolated rainfall off of the roof.



Infiltration Trenches are narrow ditches filled with gravel that intercept runoff from upslope impervious areas. They provide storage volume and additional time for captured runoff to infiltrate the native soil below.



Continuous Permeable Pavement systems are excavated areas filled with gravel and paved over with a porous concrete or asphalt mix. Normally all rainfall will immediately pass through the pavement into the gravel storage layer below it where it can infiltrate at natural rates into the site's native soil. **Block Paver** systems consist of impervious paver blocks placed on a sand or pea gravel bed with a gravel storage layer below. Rainfall is captured in the open spaces between the blocks and conveyed to the storage zone and native soil below.



Rain Barrels (or **Cisterns**) are containers that collect roof runoff during storm events and can either release or re-use the rainwater during dry periods.



Rooftop Disconnection has downspouts discharge to pervious landscaped areas and lawns instead of directly into storm drains. It can also model roofs with directly connected drains that overflow onto pervious areas.



Vegetative Swales are channels or depressed areas with sloping sides covered with grass and other vegetation. They slow down the conveyance of collected runoff and allow it more time to infiltrate the native soil beneath it.

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Bio-retention Cells are depressions that contain vegetation grown in an engineered soil mixture placed above a gravel drainage bed. They provide storage, infiltration and evaporation of both direct rainfall and runoff captured from surrounding areas.



Rain Gardens are a type of bio-retention cell consisting of just the engineered soil layer with no gravel bed below it.

Figure 105. Example of alternative techniques, LID devices which can be implemented in EPA-SWMM software (extracted from (L. A. Rossman 2015))

These techniques have different scopes of application and different objectives. Their use should be thus in concordance with the catchment's context and the local urban planning. Figure 106 gives recommendations according to the wanted control stage.



Figure 106. Recommended SUDS devices at different stages of runoff control (those in brackets are usually not considered as SUDS) (adapted from (Butler and Davies 2010))

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In the PhD thesis of (Chamoux 2003), three scenarios of adaptation are compared for two urban catchments located in Antibes, near Nice. The first two scenarios include "curative alternative techniques" while the third one is dedicated to "preventive alternative techniques". However, the expression "alternative techniques" defines in that thesis techniques which are not based on sewer network rehabilitation and resizing. Underground storage tanks are used as a reference, with a large extent in the curative case, and at the parcel level for the preventive case for new constructions.

Table 16. Description of alternative techniques according to several constraints (extracted from (Chamoux 2003))

Local constraints	Real estate pressure		Type of traffic		Hydro- graphic property		Pollution sensitivity		Network			
Alternative techniques	Urban area*	Suburban area	Scarce urban area	Quick and free-flowing traffic	Slow and dense traffic*	Parking area*	Permanent watercourse	Dry valley*	Impervious sole or existence of groundwater*	Pervious sole without aroundwater	Existence of stormwater drainage network*	Lack of stormwater drainage network
Oversized	•••	••	•						_	_		_
sewer**												
Open-sку basin	•	••	•••		_		—		—	—		
Undergrou nd basin**	•••	••	•				_			_		▼
Roof												•
storage**	•••	•••	•••									
Soakaway	••	•••	•••	_		▼	_		▼		_	
Infiltration							_		T			
trench									•			
Swale	•	•••	•••	—	—	▼	—		▼		—	
Storage			•									
tank**												
Pervious	•	••	•••				_		_	_	_	
pavement	-			-	•			_				-

• feasible; •• suitable depending on the cost; ••• fully suitable;

- technique independent on the criteria;

▲ advantageous technique and ▼ disadvantageous technique regarding the criteria;

* local constraints in the French Riviera coastal cities

** alternative techniques feasible in the French Riviera

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The city of Antibes is subject to the same constraints than Nice but benefits from a greater experience in stormwater management. Several European projects have made the city aware of its vulnerabilities and opportunities. For example, the Rainpol platform has been used in Antibes since 2012 (RainGain 2014).

Regarding the constraints met in the French Riviera cities, four techniques prove to be suitable for urban stormwater management (Chamoux 2003): oversized sewer, underground basin, roof storage and storage tank. It should be noticed that these techniques are mostly structural and quite far from what we call "alternative" nowadays. Indeed, roof storage here is not green roof, but a sort of small open-sky reservoir on the roof. This shows the vocabulary evolution and the need for accurate explanation when referring to "alternative techniques".

Alternative techniques for urban stormwater management have greatly evolved for the past decades, as well as their terminology (Tim D. Fletcher et al. 2015). Different acronyms were created to define specific techniques. The challenge for worldwide urban hydrologists is to understand each other and to integrate the general concepts to the local conditions. Indeed, SUDS, LIDs, BMPs, WSUD and Co are widely cited in the literature. New terms have emerged as the considerations have evolved, integrating wider interests within the urban stormwater management scope. Figure 107 presents the evolution of included concerns in urban stormwater management with the corresponding terminology that has emerged worldwide. Position in time and in included concerns is approximated according to the information presented by the review (Tim D. Fletcher et al. 2015).

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Figure 107. Evolution of the integration of urban drainage management concerns and terminology (adapted from (Tim D. Fletcher et al. 2015))

In another part of France, the city of Lyon has chosen to take a strong policy direction towards an integrated stormwater management. Urban planning is connected to an analysis of different stormwater management scenarios (Sibeud 2013). Main reflection aspects are presented and could be taken as frame for other cities.

Vegetative swales have been experimented in the suburban area of Rouen, in the Northwestern part of France. Road runoff is collected and analyses show that vegetative swales are efficient to mitigate the road runoff pollution (Leroy et al. 2017).

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Many publications highlight the importance to consider several criteria prior to any technique selection, especially economical aspects (Matzinger et al. 2016; Chamoux 2003). Indeed, construction works and urban planning belong to public authorities' duty and no commercial budget can be involved.

Another aspect of mitigation measures should be examined: the spatial distribution of BMPs in a study-area. In fact, traditional approaches consist in a centralized implementation, but emerging trends propose distributed approaches. A study has been made in four catchments located in the U.S. North-Eastern coast with a forested catchment serving as a reference, two with centralized BMP and one with distributed BMP. Results show that hydrological response is improved by distributed BMP, however the forested conditions cannot be met (Loperfido et al. 2014). Therefore, land cover plays the most important role in runoff volumes production. Moreover, the use of any BMP, such as rainwater harvesting, cannot prevent sewer overflows in case of heavy rainfall, even in a distributed manner (Petrucci et al. 2012).

When looking at Nice's situation and context (see Chapter 2), it is clear that previously presented alternative techniques are not adequate for different reasons:

- Lacking empty space: the real-estate pressure is very high (approximately 4000 €/m²).
- Dry weather in summer: impossible for all types of vegetative techniques.
- <u>Highly insufficient storage or infiltration capacity:</u> excessive amounts of runoff volumes are produced in case of heavy rainfall, storage tanks capacity is largely exceeded, furthermore alternative techniques.
- <u>Rainy days scarcity</u>: only few rainy days are recorded per year in the French Riviera (in the order of 85 days per year in average in Nice).

Other types of adaptation should be considered.

B.2.3. Drainage system management and real-time control

Sewerage systems are often operated with fixed elements, in a way which will remain the same without any intervention of the operator. Nevertheless, another way to operate a system in an adaptive and flexible manner is the real-time control (RTC) of a sewer system.

This concept is defined by Schilling et al. (1989) (in (Butler and Davies 2010)) as the situation when "process data, which is currently monitored in the system, is used to operate flow regulators during the actual process".

Real-time control includes dynamic rules designed to take decisions and control the flow in the drainage network according to its current state. For instance, gates, pumps or movable weirs can be dynamically controlled according to the current flow or water level at one or several locations in the network. The aim of such active rules is to enable a better utilisation of the capacity of the sewer system and limit adverse impacts, such as pollution by combined sewer overflow (CSO) and flooding through manholes.

The principle in practice, as explained by (Manfred Schütze et al. 2004) in Figure 108, includes the use of sensors, to monitor the current state of the network, actuators (or regulators), to regulate the process; controllers, to control the actuators and achieve a minimum deviation from the desired set point; and data transmission systems for the communication (measured data and signals) between the different devices.



Figure 108. RTC control loop (reproduced from (Manfred Schütze et al. 2004))

The main types of sensors are rain gauges, water level gauges, flow gauges and quality gauges. It is obvious that these devices must be reliable while they continuously record and transfer data. The actuators can be equipment such as pumps, gates, weirs or valves, for example. Each actuator is associated to a controller, which can be continuous or discrete. Several ways of discrete control exist, like two-point on/off or open/closed and three-point control, which has been implemented to overcome the high frequency of state change in a two-point control. One example of a continuous controller is the PID (proportional-integral-derivative) controller, leading to reduced versions, such as P, PI and PD. The data transmission systems may be by wire or wireless, depending of the available possibilities.

Real time control systems are classified according to their degree of automation (manual, supervisory or automatic) and depending on their level of complexity (local, global or integrated) (Manfred Schütze et al. 2004). RTC systems are manual when the action of an operator is required to set the actuators; supervisory if the operator only needs to define the controllers set-points; and automatic when no operator is needed to perform the control. At a local scale, the required measurement is carried out at the actuator location; while at a global level, measurements can come from other parts of the network, or a central control room can centralise the information coming from the whole network and coordinate the actions. The next step is the integrated control, still at the stage of investigation, and whose purpose is to take coordinated decisions according to the current situation beyond the limits of the sewer system. The aim would be to be able to operate the drainage system with regards to the treatment plant situation, the wastewater production and the current state of the receiving water bodies.

In addition, RTC systems are structured in three hierarchical levels, as seen in Figure 109.



Figure 109. Various levels in RTC systems (reproduced from (Manfred Schütze et al. 2004))

According to (M Schütze and Haas 2010), it has to be noticed that RTC has been known for several decades and is however not widely used in practice. Designing the rules is indeed not straightforward and even though global control algorithms exist, a process of tests and result comparison is necessary to develop the best RTC rules.

RTC implementation is not excessively expensive when existing network structure and devices can be adapted to the new strategy (G Dirckx, Schütze, Kroll, Thoeye, Gueldre, et al. 2011; Geert Dirckx, Assel, and Weemaes 2014). New trends have been developing for several years at the management level presented in Figure 109. These systems are known under the name of "global real time control" including predictive control and forecast model (Joergensen et al. 2014).

In France, Suez-Environnement group is involved in several innovative cases of real-time integrated management of drainage systems (Andréa et al. 2013; Komorowski, Ahyerre, and Schoorens 2014; Jérôme Schoorens et al. 2014; Palenc et al. 2016; J Schoorens et al. 2016; Laplace et al. 2016; Bourgogne et al. 2007). The French terminology is "gestion dynamique (GD)" which can be translated as "dynamic management". This expression refers to the management level of RTC oriented towards a global strategy. Instead of using a set of presimulated scenarios which represent a finite number of possibilities of reaction, the objective is to design global predictive management method. Dynamic management relies on four regulation strategies (Andréa et al. 2013; Komorowski, Ahyerre, and Schoorens 2014):

- In dry weather conditions, the system is in a "standby" strategy state. The control devices are in a steady position to drive the dry weather flow to the wastewater treatment plant. In general, no retention nor draining is carried out and no spillage is observed. The system performs predictive computations but no specific regulation instruction is applied.
- In rainy conditions, the system is activated in "depollution" mode. This is the usual strategy in case of rain event when no extreme intensities are expected. In this case, instructions are given to prevent spillage by optimising the utilisation of the storage capacity of the drainage system and by maximising the flow driven to the wastewater treatment plant.
- In the case of a heavy rainfall forecast, if the system was in "depollution" mode, the applied strategy is the "quick draining" mode. The objective is to empty the drainage system quickly to dedicate the whole storage capacity to the forecasted event. In this way, a part of the exceeding volume can be stored and the drained area can be protected from potential flood risk.
- In case of **expected flood risks**, or if the "quick draining" could not empty the system before an important rainfall event, the strategy would be to set on "flooding". In that case, the operator takes over the control of the system manually. Usually, the hydraulic structures are put in safety positions to prevent any worsening in the flooding process.

The system is updated every five minutes and centralizes the radar rainfall data, the measures of the sewer network's state, the 1D hydrodynamic model built with InfoWorks (Innovyze 2017a) and its modelling results for the next three hours, and the optimisation engine. The selected strategy is submitted to the operator for validation. Finally, according to the operator decision, instructions are directly transmitted to the control devices of the sewer system (Andréa et al. 2013).

Dynamic management has been applied in Bordeaux since January 2013. The evaluation of the method in terms of hydraulic performance is done by a volume balance assessment. For each rainfall event, two variables are stored: the stormwater volumes which were treated at the wastewater treatment plant (V_T), and those which were discharged to the environment without treatment (V_D). An interception coefficient (%) is proposed as efficiency calculation (Komorowski, Ahyerre, and Schoorens 2014).

$$I = \frac{V_{\rm T}}{V_{\rm T} + V_D} \tag{21}$$

The feedback provided after one year of operation gave interesting results with interception results between 51% and 80% and a global reduction of 30% of the discharged polluted volumes to the environment (Komorowski, Ahyerre, and Schoorens 2014).

The implementation of such global management system includes important practical consequences and restructuring. Operators should be trained to use and interact with the dynamic management system.

After the first successful experiment in Bordeaux, the same dynamic management system is implemented in other cities in France, like in Saint-Etienne (Palenc et al. 2016), in Biarritz

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(Jérôme Schoorens et al. 2014) and in Marseilles (Laplace et al. 2016). Coastal cases (Biarritz and Marseilles) have greater interests in the prevention of bathing waters pollution and use coupled modelling systems between the sewer system and the seawater system.

B.3. Forecasting towards real-time management: tools and existing methods in the context of rainfallgenerated-overland flow

Urban areas have been developed to enable a fast outflow of stormwater which produces concentration of important volumes at the catchments' outlets. Urbanization and urban density may be aggravating factors in urban flood occurrence. When considering Mediterranean climate, violent events with short durations are the main cause of this type of problem (Andrieu, Browne, and Laplace 2004). Urban floods generated by runoff processes have an extremely sharp dynamic because of the reduced extent of urban catchments and of the quick and intense rainfall events. These phenomena are called "flash floods". Within these quick processes, fast street drainage might appear to be convenient, however the suddenness of overland flow is very often devastating even deadly. This is why being able to forecast such events occurrence and vulnerable areas location is of utmost importance.

Three types of approaches can be distinguished while looking for intense-rainfall-generatedflash flood forecasting (Henonin et al. 2013): (1) empirical approaches consisting in analysing historical rainfall data and emergency services intervention data; (2) methods relying on modelling and pre-simulated scenarios use; (3) real-time approaches which implies model development to be able to provide simulation results quickly enough before the event starts.

Different operational methods have been set-up in France, especially in the South-East-Mediterranean Region, prone to seasonal and intense precipitation regime. The AIGA Method (Adaptation d'Information Géographique pour l'Alerte en crue) can be translated as "geographical information adaptation for flood warning" have been developed by Météo-France and IRSTEA (formerly Cemagref) (Lavabre and Grégoris 2005).

Complete necessary datasets for real-time forecasting of flash floods are summarized by (René et al. 2013) in Table 17. In this table, the different types of data are divided into two categories: historical data which have been recorded from previous events, and real-time data which are currently recorded and accessible at any moment. Data and models can be used at several steps of the three kinds of approaches.

	Types	Empirical	Pre-simulated	Real-time
		scenario	Scenario	simulation
	Rainfall	Sets threshold	Catalog creation	Model creation
	Network	_	Adduction	Adduction
	Water level and flow			
ıta	Topography	Sets threshold	Calibration	Calibration
al da	Land use	_	Overland flow	Overland flow
orica	Operational data			Development
listo	Radar	-	Development	Development
T		_	Development	Development
			Development	Model creation
		Sets threshold	Catalog creation	
	Precipitation forecast	Enables	Enable scenario	
Ð	(model and/or radar)	scenario	selection	Madalianuta
dat	Painfall	case of an		Model Inputs
ime	Rainiai	exceeded		
eal-t	Flows	threshold		Assimilation for model
Å	Water levels			
				upuales
	1D, 2D, 1D/1D, 1D/2D,	-	Scenarios catalog	Real-time modelling
dels	1D/1D-2D		creation thanks to	
Mo			simulations	

Table 17. Description of data use according to selected approach for flash floods forecasting (reproduced from (René et al. 2013))

The first approach consists in determining scenarios thanks to an analysis based on the return of experience. A good example of this method has been applied in Marseilles where diagrams have been developed to determine the level of risk in the city according to the forecasted cumulative rainfall. Four different levels of risk have been defined at four threshold-values from typical consequences in the city and its drainage system (Laplace, Garro, and Deshons 2007; Laplace and Deshons 2009). The analysis has been even done deeper with the definition of

the necessary number and location of operators in the city to handle the consequences and to achieve a thorough event reporting. This approach in Marseilles relies on the experience and observations gathered since 1985 and on the continuous assimilation of rainfall events data and their consequences on the city. This system enables the SERAMM (belonging to Suez Environnement) to manage rainfall events in a fast and robust way without having to use modelling to get conclusions on the city safety.



Figure 110. Graph linking rainfall intensity, cumulative precipitation and hazard classification (SERAMM, Marseilles, extracted from (Laplace, Garro, and Deshons 2007))

However, all cities willing to improve their management of rainfall events and stormwater do not always benefit from such good quality and long-time data base in terms of historical events and their consequences on the city hydrological response. In that case, modelling tools might be very useful to represent the hydrological processes. A model of understanding could be built to figure out rainfall consequences on the city and its natural and artificial hydrographic networks. Even if one could expect more accurate results from a more complex approach, it strongly depends on the quality of the available data. The selection of the method should be done according to the needs of the study and the expectations of the results use, available data, spatial extent of study-area and temporal needs in terms of result use. Each approach features some limits which should be quantified. These limits are presented in Table 18.

Approach	Limits
Empirical scenario	 Lack of observations of past flood events Changing urbanization which might change flood prone areas location Uncertainty on rainfall data
Pre-simulated scenario	 Inadequate rule of scenario selection Scenario catalog not detailed enough Problems in model calibration and validation Uncertainty on rainfall data Problems in obtaining real-time data
Real-time simulation	 Problems in model calibration and validation Uncertainty on rainfall data Lack in data, adapted technology to get necessary measures or lack of technical workers Problems in obtaining real-time data

Table 18. Limits to take into account for each approach (extracted from René, Djordjević, Butler, Madsen, & Mark, (2013))

Thus, it is strongly necessary to determine opportunities and limits prior to any approach selection among those three kinds of method. However, an empirical approach might be followed anyway in parallel with any modelling approach. Also, a real-time modelling approach would be efficient only after a simpler model would be previously successfully calibrated and validated. Of course, the running duration should be improved to meet real-time modelling challenges. In conclusion, the first two approaches should be selected and followed when starting to study an urban area without specific already-existing method or tools. A real-time approach should be chosen only after significant knowledge has been gathered for the stormwater management of the selected urban area.

B.4. Crisis management and planning and risk analysis

Supervision tools and control centres have emerged in cities for many operational purposes, including the supervision of water networks. When heavy rainfall events lead to urban pluvial flood, if the control of overland flow and volumes is lost, the operation is at a crisis state and crisis management procedures should be previously defined. Important amounts of information should be available to handle the crisis. Figure 111 and Figure 112 show examples of water networks supervision centres with latest equipment for crisis management.



Figure 111. Picture of the supervision centre RAMSES in Bordeaux (SALVAN, 2015)



Figure 112. Picture of the supervision centre of Lyonnaise des Eaux in Mougins (SALVAN, 2015)

In Marseilles, as presented previously, rainfall forecasts are used in combination with graphs linking forecasted cumulative precipitation and rainfall intensity to hazard. This relationship is directly used in the management of on-night / week-end duty employees. The city is divided into a number of areas of interventions where employees are allocated to check known critical zones. The number of areas increases with the gravity of the expected phenomenon. This means that for heavy rainfall forecasts, on-duty employees are dedicated to smaller areas. Moreover, the service in charge of the drainage system (SERAMM) collaborates with the municipality services.

In Nice, emergency procedures related to natural hazards, including floods, have been revised recently. The October 3rd 2015 event has highlighted the need for more preparation and that a formalised organisation is of paramount importance (Dorgigné et al. 2017). The crisis management approach has evolved significantly. However, there is no specific collaboration between the drainage system, stormwater management and risk management services yet. On top of that, it should be stressed out that recent responsibilities transfers between the municipality and the NCA Metropolis add up to the complexity to clearly define who does what. More concertation and common planning could improve the reactivity of the municipality services in case of a new crisis.

Part C Guidelines to improve and capitalise local knowledge

Improvements may be done regarding several aspects. A selection of the key aspects is presented in this part. These aspects were chosen by the author from a wide technological and practical watch. Useful implementation could be planned in Nice as well as in other Mediterranean cities featuring comparable situation.

The first aspect concerns the improvement of knowledge of past events by implementing a reporting routine. Then warning threshold could be implemented at different levels, from the instantaneous rainfall intensity to the forecasted cumulative precipitation. Finally, stormwater quality is a developing topic in Nice which would benefit from wider synergies.

C.1. Historical precipitation facts and event reporting

The previously used example of Marseilles' stormwater management and planning relies on a robust and systematic event reporting for several decades (Laplace, Garro, and Deshons 2007). After a flood crisis, a report is produced to keep in memory the detailed description of the rainfall event and the observed consequences. The implemented mechanism to handle the crisis is also included in the report. In this way, knowledge and management practice can be improved by implementing a database and by continuously performing event analyses (Laplace and Deshons 2009).

Recently, the public has been able to produce and share masses of information such as photos and videos worldwide. Well documented and well taken, images of flood events represent valuable data sources for hydrological and hydraulic studies. With suitable preprocessing tools, numerous pieces of information might be extracted from photos and videos, such as flood extents, water levels and flow rates (Coz et al. 2016). Crowdsourcing is a new trend and citizen science initiatives are reviewed through three projects taking place in France, Argentina and New Zealand. The authors insist on five conditions which should be met to successfully collect data from citizens: (1) a clear and simple procedure, (2) suitable data collecting and processing, (3) an efficient communication plan, (4) support from local stakeholders and (5) public involvement (Coz et al. 2016).

Another way to collect historical information about ancient events is proposed in a European project (Aménag'eau) near Bordeaux (Luneau 2017). It consists in visiting retirement homes to collect the memories of elderly people. This method could be beneficial when poor data is available about consequences of past events.

In Nice, comparable approaches could be implemented. However, new tools and databases could be preferred to the concept of report. It would be easier to look for information such as rainfall, characteristics, consequences, network state, conclusions, what worked and did not, and details about interventions from the rescue services (SDIS) and from the city.

Furthermore, the city of Nice possesses numerous CC-TV devices for safety and road control. Depending on the law regulations, a partnership could be imagined between the municipality or the NCA metropolis and the police department to take advantage of this valuable source of information. Photos and videos could be produced by new devices or existing monitoring police cameras. Moreover, drones could be used to collect global flood extents. This source of information would be very valuable for later analysis of flood events.

C.2. Warning threshold definition for rainfall stations

This part gets inspiration from a research work carried out in the city of Marseilles for two decades by the SERAMM company. Rainfall warning thresholds have been locally defined in function of the history of the city's response to precipitations. A strategy of organisation of the on-night / week-end duty employees has been developed and implemented (Laplace and Deshons 2009; Laplace, Garro, and Deshons 2007). This method is based on the examination of the intervention register of the operator company of the sewer system and of the navy fire department of Marseilles. Relationships between cumulated precipitation, rainfall intensity and consequences in the city are established. This enable to set-up direct links between forecasted precipitations and potential risk level in the city.

This approach is very valuable and could be implemented in Nice, following the same principles. In the case of Nice, three types of stake-holders are likely to take actions in heavy rainfall conditions (Figure 113). First interventions are done by the sewer network operators, on the field when rainfall conditions enable it, to regulate the network. When rainfall intensity starts to be hazardous for population and city assets, city authorities take actions and are responsible for instance for road closing decisions or population evacuation. Lastly, the departmental service for fire and rescue (SDIS, Service Départemental d'Incendie et de Secours, in French) is called to take emergency actions to rescue people endangered.



Figure 113. Pyramid of stake-holders on the sewer network and on the city in case of heavy rainfall

In order to be able to determine a tendency allowing to link precipitation and observed consequences in the city, intervention registers are essential sources of information. By analysing them together with rainfall data, the hydrological response of the city to historical events could be determined.

SDIS 06 services have communicated a list of dates classified in function of the gravity of the interventions which were necessary due to intense rainfall. Consequences in terms of flooding and landslides are mixed here. Four categories have been defined:

- 1. Low
- 2. Medium
- 3. Important
- 4. Major

In a first approach, these dates have been confronted to observed daily precipitation at Nice-Airport station (operated by Météo-France) in order to define classes of cumulative precipitation (defined by the maximum and minimum observed values) leading to each category of gravity (Table 19).

Table 19. Dates of recorded and classified events (provided by SDIS 06 services) and corresponding observed cumulative daily rainfall (in grey: below the 40mm/d threshold) (Nice-Airport rainfall station operated by Météo-France).

CLASSES	LOW	MEDIUM	IMPORTANT	MAJOR
	06/06/2000	24/10/1999	05/11/2000	4 et 5/11/1994 (Var flood)
	23/11/2000	06/11/2011	03/10/2015	30/09/1998
Dates	04/06/2012	26/10/2012		04/11/2014
	29/09/2012	16/01/2014		04/11/2014
		10/11/2014		
Observed daily rainfall (Nice Airport)	40.2 – 76.2 mm/d	65.8 – 108.2 mm/d	76.8 – 111.9 mm/d	116.6 – 159.7 mm/d

Figure 114 presents in the x-axis the four above-defined event classes and in the y-axis the observed daily cumulated precipitation. For each event class, the lowest and highest values are plotted at the extremities of a segment representing the interval of values. The circled value in between the lowest and highest values was first set as the average of the interval to represent the corresponding type of event. However, when the classes are overlapping, the average is not selected anymore. A value was selected for each type in concordance with other classes.

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Figure 114. Analysis of SDIS intervention data since 1994

This graph shows that intervals "Medium" and "Important" are very close in range. Also, a significant part of the "Low" interval is included in the "Medium" interval. For these reasons, the selected representative values have been slightly moved from the average of each interval.

In a second approach, the analysis is deepened by looking at the 4min-time-step. The selected rain gauge is the PLNIC13 located in the lower Magnan valley. When data is not available, PLNIC20 located near the airport is chosen. For each event belonging to the records (start in 2010), the event duration, the maximum intensity (4min) and the cumulative precipitation are extracted. The meteorological context of the previous days is also examined. The details are presented in Table 20.

Table 20. Details of the rainfall events which caused rescue services interventions (SDIS 06) in Nice since 2010 (rainfall data from PLNIC13 or PLNIC20 if not available)

Date	Dur ation	lmax (mm/h)	Total precipitation (mm)	Meteorological context
06/11/2011 (no data for 05/11)	144 min	36	15.2	3 rainy days (100mm)
04/06/2012	80 min	75	16.8	Dry weather
26/09/2012	38 min	354 (mistake)	45	Rainfall on 24, 26, 29 et 30/09

Date	Dur ation	lmax (mm/h)	Total precipitation (mm)	Meteorological context
26/10/2012	160 min	90	43.4	Dry weather, light rain in the morning
17/01/2014	11h	78	104.4	1 rainy day
04/11/2014 (2 nd peak)	148 min	114	73.6	1 st peak during the night, 2 nd around noon
10/11/2014 (<u>PLNIC20)</u>	60 min	210	60.4	Heavy rainfall on 4 and 5/11 and on 9/11 night, light discontinuous rain in the morning on 10/11
03/10/2015	6h (in total with 2h of main peak)	97.5	107.5	Light rain in the afternoon

Other rainy days where extracted from the daily data (Météo-France) with a cumulative precipitation exceeding 40 mm which were not listed in the SDIS records. These events are examined as well (Table 21). The objective is to determine which trigger leads to the necessity of the rescue services intervention.

Table 21. Details of some rainfall events causing a daily cumulative rainfall exceeding 40 mm without leading to rescue services intervention (SDIS 06) in Nice (rainfall data from PLNIC13 or PLNIC20 if not available)

Date	Dur ation	lmax (mm/h)	Total precipitation (mm)	Meteorological context
31/10/2010	364 min	30	61.6	25.6 mm the day before
21-23/12/2010	3 days	36	102.4	Dry weather
15/02/2011 (PLNIC20)	Scattered rain over 24h	18	40	Some mm the day before

Date	Dur ation	lmax (mm/h)	Total precipitation (mm)	Meteorological context
05/06/2011 <u>(PLNIC20)</u>	60 min	54	23	Some mm the two previous days
10/04/2012	Scattered rain over 24h	18	40	Dry weather
27/11/2012	Scattered rain over 24h	24	54.6	20.2 mm the previous day
19/01/2013	Scattered rain over 24h	9	43.2	Dry weather
06/03/2013	Scattered rain over 24h	6	40	Some mm
04/01/2014	284 min	45	20	Dry weather and very light continuous rain on 4/01 morning
09/11/2014 (<u>PLNIC20)</u>	8h	42	40.8	Dry weather
14/11/2014	8h30	24	44	Dry weather

Most reported events in Table 21 took place after a dry weather period or very light rain. The meteorological context seems thus to be one of the main triggers to increase the gravity of rainfall events and their consequences in terms of flood or land slide. Indeed, the soil saturation is a crucial parameter in the hydrological processes and saturated soils increase runoff volumes production.

These results are preliminary results and should be deepened and enriched with more accurate and detailed intervention data. Also, flooding and landslide interventions should be separated to put a stronger focus first on floods. Landslide could be a second step of such analysis. Moreover, the number of recorded dates is limited with only 14 recorded events. Instead of the daily reference used here, the scale could be the intervention, which would be classified according to its gravity in terms of type of intervention, number of vehicles and fire-fighters involved, number of rescued people. The accurate record of address and hour of the day would also be very useful. Future analysis would benefit from wider records and detailed registers. For example, rainfall thresholds triggering landslides could be estimated like in other studies (Fouchier et al. 2015), if the specific interventions were clearly identified.

The number of calls and number of actual interventions of the three categories of stakeholders could be used to enrich this analysis. Especially, the interventions of the city authorities should be considered.

This approach can be linked to a previous study of runoff generation in Nice which used the concept of return period to define rainfall scenarios of 30-minute-constant-rainfall (Batica and Gourbesville 2014).

Table 22	Rainfall	scenarios	extracted	from	(Batica	and	Gourbesville	2014)
10010 22.	rtannan	0001101100	0/11/00/04		Dullou	ana	00010001110	2011).

Return period	Rainfall intensity (mm/h)
T10	43.6
Т50	59.0
T100	65.5



Flood Maps of Nice with Current Landscape

Figure 115. Flood map produced with T10, T50 and T100 rainfall scenarios (Batica 2015)

In concertation with the Department of Risk Prevention and Management of Nice and taking into account the previous flood maps (Batica and Gourbesville 2014) and the latest analysis of the rescue interventions (presented in this paragraph), pre-alert rainfall threshold were estimated for Nice's virtual rain gauges on the Rainpol platform (Dorgigné et al. 2017).

Table 23. Warning thresholds and corresponding potential consequences and actions that should be taken (adapted from (Dorgigné et al. 2017)).

	1 st level	2 nd level	3 rd level	4 th level
Level of precipitation accumulated within the hour	25 mm	40 mm	50 mm	70 mm
Type of possible phenomenon	Important rainfalls requiring more vigilance	Heavy rainfalls that can cause significant but localized and temporary run- off	Very heavy rainfalls which could lead to shelter and the initiation of safety measures	Exceptional rainfall which can generate relief for people and strongly impact the territory
Action	Follow meteo preoccupante	 1-Services vigilance 2-Information of vigilance to the populations 	 1-Mobilization of personnel 2-Triggering of safety procedures 3-Triggering cell of vigilance of the Communal Center of Crisis 4-Population information 	 1-Mobilization of personnel 2-Pre-positioning of on field dispositions 3- Triggering cell of vigilance of the Communal Center of Crisis 4-Population information

In this way, the next hour forecast can trigger the alarm and on-duty teams can prepare for interventions. These thresholds should be further refined after one year of operation and more detailed intervention records.

C.3. Towards a better understanding and modelling of stormwater quality

The original aim of this research work was to consider stormwater quality as well as flooding issues and to propose a global methodology to improve the protection of the receiving waters. However, due to lacking network quality data, water quality was not included. Furthermore, the news throughout the research work, especially the October 3rd 2015 event, made the author focus more on flooding issues. This paragraph presents shortly two methods that were implemented in other comparable cities.

Numerous studies of combined sewer optimisation to reduce combined sewer overflow can be found in the literature (Mulliss, Revitt, and Shutes 1996; G Dirckx, Schütze, Kroll, Thoeye, De Gueldre, et al. 2011; Reidy 2014; Joergensen et al. 2014) and a complete review of the impacts of polluted spillages on receiving waters was published (T.D. Fletcher, Andrieu, and Hamel 2013). Two integrated modelling approaches are selected here because of their similar coastal situation that they share with Nice (Jérôme Schoorens et al. 2014; Laplace et al. 2016).

A first study-case is presented in Biarritz with a coupled modelling system between the sewer network the ocean numerical models (Jérôme Schoorens et al., 2014). Five rainfall events are used to investigate on solutions to reduce discharge to the ocean. Several solutions are tested and finally combined to obtain a reduction of the polluted discharges by nearly 40%. The second case is located in Marseilles with a background of evolving system towards an integrated and dynamic management of the drainage system with limited discharges to the environment (Laplace et al. 2016). Both cases use a 1D hydrological and hydraulic sewer network model built with SWMM5 software (Lewis A Rossman 2015) coupled with a marine model including a wave code and a pollution loads dispersion code which uses the outflows of the sewer network model as one of the input data. The implemented strategies and overall management of the system relies on the central supervision which was already presented in Part B of this Chapter. The implementation of such integrated systems is divided in several steps which can be summarized as follows (Laplace et al. 2016):

- 1. Implementation of an operational model of the drainage system, including storage tanks, control devices and wastewater treatment plant inputs and outputs.
- 2. Addition of an operational water quality module.
- 3. Coupling with a receiving water model accounting for interactions with the sewer network and the watercourses, able to represent pollution loads dispersion in real-time.

On-going research carried out in Nice about bathing waters protection are promising. However, the current sewer network model needs to be adapted to meet real-time operation needs. Mike URBAN (DHI 2014b) includes a pollution transport module (MOUSE TRAP (DHI 2010)) able to account for surface runoff quality, with the build-up and wash-off of sediments; sediment transport and advection-dispersion (DHI 2016e).

Conclusions and perspectives Part D

D.1. Synthesis

Many engineering approaches exist with a wide range of stormwater management orientations and very often combinations of the previously presented possibilities of retention tanks, SUDS, RTC strategies and forecasting methods. In fact, the choice of the position in this spectrum will be made by decision-makers and executive councils of cities or conurbations.

In the legal framework of stormwater management in France, different points of view exist depending on the local context, historical events and local topography. Because of the decentralised administrative structure of France, local decision-makers are able to develop their own methods, which is an opportunity to compare the implementation and consequences of different techniques. For example, the cities of Lyon and Bordeaux have taken different orientations in terms of stormwater and urban drainage management. While in Lyon, SUDS and urban planning have been selected as main direction, in the city of Bordeaux, dynamic management and complex supervision systems have been implemented. This show that each city is led to an adapted solution to the local context. Moreover, the frequency or more importantly the date of the last dramatic event shapes the local public policies of stormwater management.

D.2. Perspectives in Nice

The status-quo of the city of Nice is interesting because no strong stormwater policy has been chosen yet. Therefore, the possibilities are open and the challenge is to define and select the most adequate strategy.

After examination of several techniques used and developing nowadays, the author finds that the situation of the city of Nice is complicated for the implementation of adaptation measures. We have seen that storage tanks are an option but would be useful more for bathing water quality issues, since in case of heavy rainfall, storage capacity would be quickly exceeded. Regarding SUDS, first the available space is still an issue, but not the only one. The Mediterranean climate is very dry in summer and the maintenance of such green areas would consume important amounts of water which is often scarce in this season. When looking at the implementation of a global RTC strategy, other obstacles were encountered. The limited number of storage basins does not offer an interesting degree of latitude and are quickly full in rainy weather. Also, most throttling devices are located in the downstream sections of the network, which corresponds to the most vulnerable areas.

Finally, it appears that given the specific climate and topographic conditions, and regarding the very limited budget allocated to stormwater management because of the very little number

of rainy days in the year, an adequate local solution would rather rely in a better protection of the population guaranteed by a better forecasting and crisis planning. Education and risk culture should be developed widely at all ages of the population, from the school to the retirement houses. Work places could also be an efficient information media for good practices in case of important flooding.

Investigations have been carried out in the framework of several European projects about Resilience (for instance the CORFU) and a flood resilience index has been established (Batica 2015). A PhD thesis treats the topic thoroughly (Batica 2015). The basic principle is to look at the city in terms of urban functions and to determine in which way the city could be resilient to a flood event and how to improve its ability to retrieve normal operation mode. This point of view represents an alternative to the desperate search for the best drainage network or the best adaptation measures. The issue is taken from the other side, the question raised is closer to the search for the best human individual and collective adaptation techniques.

D.3. General recommendations

Finally, it is necessary to build local stormwater management protocols according to the local needs and constraints.

Fast and detailed modelling trends are complementary and may be used in crisis phases and prevention phases, respectively. Prevention and post-crisis phases, there is enough time for modelling development and calibration. However, in the crisis management phase, fast tools and previously developed scenarios or real-time integrated decision support systems seem necessary.

To improve stormwater management and protect population and belongings, knowledge capitalization is of utmost importance to improve local risk culture and population education which will know how to react in a resilient city.

General conclusion and perspectives

This thesis is an exploratory research work regarding stormwater management and its modelling with a strong focus on Nice city, France. This study area has been chosen as a representative case of Mediterranean cities where sudden pluvial floods occur and for which population and assets protection is a major challenge. Recent heavy rainfall events, such as the impressive storm which occurred on October 3rd 2015, have shown the vulnerability of Mediterranean urban areas and the complexity to properly react during the crisis, from the citizen level, to the local authority management. Indeed, the quickness and the intensity of such events do not let room for improvisation.

On the other side of the rainfall event spectrum, the question of the stormwater pollution is raised, with important impacts to receiving waters representing significant threats to the environmental ecological state and the local life quality, thus important economic impacts on the touristic cities of the French Riviera.

Writing a true conclusion of this research work is a difficult task given the numerous evoked aspects about the issue of pluvial floods in urban areas and the remaining open questions. However, the conclusions can be presented regarding two main axes: the research and the practical aspects. These two sides cannot be disconnected as operational procedures should take benefit from innovations and researchers should make the effort to provide simplified explanations to the public.

Part A Research aspects: an innovative approach to model closer to the reality of physical processes

The review of the context in Nice presented in Chapter 2 highlighted that even though important amounts of information are available, the location of measurement stations does not always meet the modeler's need. Furthermore, the quality of the data depends on the maintenance quality and frequency. For example, the analysis of the rainfall regime in Nice, difficulties have been met in the local rainfall time series, with major gaps and incoherent values.

An existing model of the global drainage system was used as a reference and the known

This thesis is an attempt to improve modelling methods to represent rainfall-runoff processes in urban areas. This particular topic is a junction between many sub-topics. The encountered difficulty has been to draw limits to this research work as it includes urban hydrology, sewer network hydraulics, stormwater pollution, data management, crisis management.

The proposed method includes a modelling approach in three steps including:

- 1. **Overland flow and topography data:** Topography data is essential in flow path definition and significantly impacts hydraulic modelling results.
- Pipe and overland flows in interaction: Sewer overflow is one aspect of urban flood issues but represents only part of flood sources. Overland flow generated by runoff should be included in flood models.
- 3. **Integrated urban pluvial modelling:** Integrated urban pluvial modelling is possible with existing tools and can represent the real processes better.

However, this approach should be further developed and improved. Indeed, when sometimes 76 hours are required to model a 2-hour-event, the main limit of the method is highlighted. The gap to real-time modelling from this basis looks unaffordable. Since the main objective of all this modelling process is to improve local knowledge and to allow especially flood protection, it seems clear that modelling cannot be the only tool to use.

Finally, it appears from this investigation that complex and integrated modelling of coupled sewer and surface interactions with the distribution of rainfall between both upstream and downstream area do not benefit to an improvement in the modelling objectives. The aim was to obtain more accurate results by taking into account overland flow processes. But to tackle model instability issues, the computation time-step is dramatically decreased, thus increasing significantly simulation duration.

Part B Practical aspects: stormwater management as a core element of urban planning and population education

This thesis aimed to expose the practical aspects related to stormwater management and pluvial flood crisis management. Chapter 5 gave a wide overview of the main techniques and practices in terms of prevention, crisis management and forecasting methods. Different points of view were brought to light depending on the local policies, specificities and historical context of rainfall events.

There is a strong link between urban stormwater management and the urban resilience aspects that have emerged for several years. After examining existing real-time systems and different types of management and configurations, it appears that there is a certain threshold after which the runoff quantity is too important to allow any control. It seems thus crucial to improve the way cities are designed and adapted to handle crisis management and protect population and belongings as much as possible during floods.

In practice, for the city of Nice as well as for similar Mediterranean urban areas, several recommendations emerge from this research work. First of all, reliable and good-quality data are essential prior to any future direction. The maintenance of the measurement networks is a key aspect to consider. Then, regarding pluvial flood events and consequences, real-time control strategy development would be limited because of the very reactive drainage system and the limited storage capacity. Moreover, even best protection measures integrated in the urban planning developments will never guarantee a zero risk for populations, material assets and urban functions. Therefore, public education and development of a "culture of risk" seems essential.

Part C Perspectives for further developments and collaborations between scientists and policy makers

Doing this research in the framework of the University of Nice made the author realize the importance of collaborative work to truly improve knowledge and to create benefit from a research work. Recommendations for further research on this topic are as follows:

- Improve the collaboration between stakeholders of the urban stormwater community, especially in France. Several laboratories have been working on this topic for many years. Further work in Mediterranean cases may benefit from this global experience.
- Simplify models rather than increase their complexity. Very often, high-resolution data are available for one type but not for all types of data. Moreover, model users may need high-level training to be able to operationally run and use these models.

Even though further research is needed, it looks also essential from the author's point of view to understand and to keep in mind that heavy rainfall events are not under our control. Enormous runoff volumes in the streets have been and will be generated by extreme rainfall events. The conclusion of this research work is not straightforward but might be as simple as this statement: "when it rains a lot, streets are flooded". This does not mean that we cannot do anything about it. This means that we should be aware of where to input most of our work to make it profitable. Most probably, cities should become more resilient and population should be educated to handle and resist extreme events. "Zero risk" does not exist and protection structures will be exceeded, one day or another. In the case of pluvial flood, as in the case of any natural disaster, best levels of population and eventually material protections would be generated by good warning systems and crisis procedures previously fully understood by the population.

A risk rises when hazard meets vulnerability: this means that when there is no way to control hazards, one should look for techniques and tools to reduce vulnerabilities. In the context of floods in urban areas, rainfall events can be forecasted in a certain extent but cannot be controlled in any way. Vulnerability should be reduced at different levels starting from the citizen up to the local or national authorities. In other words, the main action-levers prone to improve population and infrastructures safety in urban pluvial flood events are related to prevention. On one side, probable consequences should be quickly determined by improving forecasting methods, to know in which catchments a strong hydrological response can be expected, and accurate local knowledge should be previously gathered, to know which warning thresholds are sensitive and which magnitude of consequences could be educated to improve their behaviour in hazardous conditions to avoid fatalities. The example of the event of October 3rd 2015 in the French Riviera is striking. Several persons have died trying to save

GENERAL CONCLUSION AND PERSPECTIVES 2

their car in flooded underground parking spaces. What has emerged as the "culture of risk" should be expanded and benefit to populations which have not met that risk yet. Collaborations with urban planning are also necessary to undertake to improve the city landscape and make city functions more resilient.

The outcomes of this research work demonstrate the fact that most theoretical information and concepts are already known for a long time. This domain does not let too much room for striking discoveries. However, true innovations lie in the capacity of nowadays modelers and operators to implement wisely known facts in a new way.

Also, community knowledge and fact memory should be capitalized better (like in other domains). Too often generations live and die with their factual memory of the most intense rainfall events and their consequences. New generations forget until the next crisis. Human communities would benefit from robust and sustainable information and memory capitalization approaches.

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Abbreviations

- 1D: one-dimensional
- 2D: two-dimensional
- **BMPs: Best Management Practices**
- **DEM:** Digital Elevation Model
- DTM: Digital Terrain Model
- GD: Gestion Dynamique
- HD: Hydrodynamic
- LIDs: Low Impact Developments
- MNCA: Métropole Nice Côte d'Azur
- SAGE: Schéma d'Aménagement et de Gestion des Eaux
- SDAGE: Schéma Directeur d'Aménagement et de Gestion des Eaux
- SUDS: Sustainable Urban Drainage Systems
- SWEs: Shallow Water Equations

Notations

- Q = discharge, $[m^3s^{-1}]$
- A = flow area, $[m^2]$
- y = flow depth, [m]
- g = acceleration of gravity, $[ms^{-2}]$
- x = distance in the flow direction, [m]
- t = time, [s]
- α = velocity distribution coefficient
- I_0 = bottom slope
- I_f = friction slope
- v: mean flow velocity (ms⁻¹)
- Δt : time step (s)
- Δx : distance between computational points in the conduit (m)
- y: water depth (m)
- τ : tangential stress caused by wall friction (Nm⁻²)
- ρ: water density (kgm⁻³)
- R: hydraulic radius (m)
- I(t) = Actual precipitation intensity at time t
- $I_E(t)$ = Evaporation loss at time t
- $I_{S}(t)$ = Initial loss (wetting and surface storage) at time t
- $I_{I}(t) = Infiltration loss at time t$
- C = Linear reservoir constant
- $y_R(t)$ = Runoff depth at time t
- I_{eff} = Effective precipitation
- A = Contributing catchment surface area
- dt = Timestep

- dy_R = Change in runoff depth
- A = Total catchment surface area
- T_L = Catchment lag time
- h(x,y,t): water depth (m)
- d(x,y,t): time varying water depth (m)
- $\zeta(x,y,t)$: surface elevation (m)
- p,q(x,y,t): flux densities in x- and y_directions (m³/s/m)
- C(x,y): Chezy resistance (m^{1/2}/s)
- g: acceleration due to gravity (m/s²)
- f(V): wind friction factor
- V, V_x , $V_y(x,y,t)$: wind speed and components in x- and y-directions (m/s)
- $\Omega(x,y)$: Coriolis parameter, latitude dependent (s⁻¹)
- $p_a(x,y,t)$: atmospheric pressure (kg/m/s²)
- ρ_w : density of water (kg/m³)
- x,y: space coordinates (m)
- t: time (s)

 T_{xx} , T_{xy} , T_{yy} : components of effective shear stress

P(t, x, y)	rainfall intensity (m/s),
------------	---------------------------

I(t, x, y) infiltration rate (m/s),

 $\vec{S}_f = (S_{fx}, S_{fy})$ roughness term (depending on the roughness law),

z(x, y) topography (m).

 Q_{UM21} : Flow from sewer to MIKE 21 grid point.

H_U: Water level in sewer system.

 H_{M21} : The average water level on the ground.

A_m: Cross-sectional area of manhole.

A_I: Cross-sectional area of inlet

C_D: The discharge coefficient

W_{crest}: crest width

H_g: ground level

Appendices

Scheme of the drainage network of Nice



APPLICATION TO NICE, FRANCE

Ferber tank



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Scheme of the main collector



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Site visit: stormwater inlets baskets



APPLICATION TO NICE, FRANCE

Site visit: Ferber tank



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Site visit: Arson tank







Superimposition of surface and underground drainage axes

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Mike URBAN results Case 1



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Mike URBAN results Case 2

