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Presented by

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Hydraulic modeling of flood risk on the scale of an African agglomeration in Cote d'Ivoire

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November 2021

DECLARATION

I, Oumar SALEH, thus declare that this thesis, titled "Hydraulic modeling of flood risk on the scale of an African agglomeration in Cote d'Ivoire," is the result of my own research except as mentioned in the references.

The thesis has not been approved for any degree and is not being submitted for another degree at the same time.

Signed:

Oumar SALEH Date: 20 November 2021

APPROVAL

This thesis has been submitted with my approval as the supervisor.

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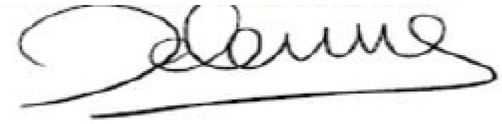

Date: 20 November 2021

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DEDICATION

To my family

ABSTRACT

In the context of urban flood control, it is essential to develop tools and methods to model surface runoff at the scale of the agglomeration.

The process of flooding is relatively common in some regions of the world, Africa remains a continent with particular concerns focused on urban flooding for the unprecedented urbanization, which increases the vulnerability of human societies to flooding. The city of Abidjan, like all African metropolises, is known for its high level of urbanization, which causes enormous damage every year during the two rainy seasons, and flooding remains a major problem today. This risk affects several districts of the capital including the Riviera-Palmeraie district although it is a residential district par excellence and inhabited by the wealthiest Ivorian class. In this study, a hydrodynamic modeling of the district was carried out in order to simulate extreme events and a better knowledge of the attributes of the flow in the urban fabric would have important impacts in a more precise mapping of the risks and thus in their prevention. The flow simulation was performed using the SW2D (Shallow Water 2D) "classical" and "porosity" computational codes developed within the HydroSciences Montpellier (HSM) laboratory. In the absence of accurate and reliable field data, the fine model is considered as a reference model to validate the porosity model. The work of this research is to set up two models, the first was the realization of a fine mesh of the district to make a first simulation and to have more precise results; the second part was the realization of a coarser mesh for the porosity model. The developed model allows to reduce the time of calculation considerably, not only in terms of calculation but also for the creation of the mesh. It is therefore fast enough to consider the production of real-time alerts. Then the model allows a comparison between the two models. The fine model allowed a hydrodynamic reference modeling to validate the porosity model. The results obtained in this thesis, present a point of divergence of a few centimeters between the two models because of the absence of high precision topographic data and the adjustment of the parameters of the porosity model.

Keywords: Flood, urban area, risk, hydraulic modeling, hydrodynamic model, shallow water 2D model.

RÉSUMÉ

Dans un cadre de lutte contre les inondations urbaines, il est primordial de développer des outils et méthodes permettant de modéliser les écoulements de surface à l'échelle de l'agglomération.

Le processus d'inondation est relativement commun dans certaines régions du monde dont l'Afrique reste un continent avec des préoccupations particulières centrées sur les inondations urbaines pour l'urbanisation sans précédent, qui augmente la vulnérabilité des sociétés humaines aux inondations. La Ville Abidjan, comme toutes les métropoles africaines, est connue pour une forte urbanisation, ce qui cause chaque année, pendant les deux saisons des pluies, des dégâts énormes liés aux phénomènes d'inondation qui reste aujourd'hui un problème majeur. Ce risque frappe plusieurs quartiers de la capitale dont le quartier Riviera-Palmeraie bien qu'il soit un quartier résidentiel par excellence et habité par la classe ivoirienne la plus aisée. Dans cette étude, une modélisation hydrodynamique du quartier a été réalisée afin de simuler des évènements extrêmes et une meilleure connaissance des attributs de l'écoulement dans le tissu urbain aurait d'importants impacts dans une cartographie des risques plus précise et ainsi dans leurs préventions. La simulation de l'écoulement a été réalisée à l'aide des codes de calcul SW2D (Shallow Water 2D) "classique" et "à porosité" développés au sein du laboratoire HydroSciences Montpellier (HSM). En l'absence de données terrain précises et fiables, le modèle fin est considéré comme une modélisation de référence pour valider le modèle à porosité. Le travail de cette recherche est de mettre en place deux modèles, la première était la réalisation d'un maillage fin du quartier pour faire une première simulation et avoir des résultats plus précis ; la seconde partie était la réalisation d'un maillage plus grossier pour le modèle à porosité. Le modèle développé permet de réduire le temps de calcul considérable, non seulement en termes de calcul mais aussi pour la création du maillage. Ils sont donc assez rapides pour envisager la production d'alertes temps réel. Ensuite le model permet de mener par la suite une comparaison entre les deux modèles. Le modèle fin a permis une modélisation hydrodynamique de référence pour valider le modèle à porosité. Les résultats obtenus dans le cadre de cette thèse, présentent un point de divergente de quelques centimètres entre les deux modèles à cause de l'absence des données topographiques de haute précision et de l'ajustement des paramètres du modèle à porosité.

Mots clés : Inondation, milieu urbaine, risque, modélisation hydraulique, model hydrodynamique, model 2D Shallow Water.

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LIST OF ABREVIATION

SRTM	: Shuttle Radar Topography Mission
1D	: One dimensions
2D	: Two dimensions
3D	: Three dimensions
AU	: African Union
AUA	: Atelier d'Urbanisme d'Abidjan
CNRS	: Centre national de la recherche scientifique
DEM	: Digital Elevation Model
DREF	: Disaster relief emergency fund
DSM	: Digital Surface Model
DTM	: Digital Terrain Model
EM-DAT	: Emergency Events Database
FIT	: Inter-Tropical-Front
FVM	: Finite-Volume-Method
GIS	: Geographic Information System
HSM	: HydroSciences Montpellier
IAHS	: International Association of Hydrological Sciences
UNESCO	: United Nation Educational, Scientific and Cultural Organization
WMO	: World meteorological organization
IHP	: International Hydrological Program
IPCC	: Intergovernmental Panel on Climate Change
IRD	: Institut de Recherche pour le Développement
ITCZ	: Intertropical Convergent Zone
LiDAR	: Light Detection and Ranging
SMS	: Surface-water Modeling System
SSA	: Sub-Saharan Africa
SW2D-DDP	: Shallow water two dimension-depth-dependant
SWE	: Shallow Water Equations
TIN	: Triangulated Irregular Network
UMR	: Unité mixte de recherche

1.1 INTRODUCTION

Flooding is one of the first natural hazards in terms of the number of people affected worldwide, with particular concerns focused on urban flooding due to unprecedented urbanization, which increases the vulnerability of human societies to flooding. For the difficulties of accessing real-time data, the numerical method seems to be a powerful approach for flood forecasting and damage mitigation. In order to combat urban flooding, a significant number of studies are conducted each year to develop software and computational codes to predict the response of watercourses to flood events. However, accurate prediction of this risk remains constrained by several parameters, including a lack of knowledge of the geometry of the area to be modeled (building map, land use), a lack of hydrological data to calibrate and validate the models, the complexity of the mesh design, a costly and generally significant computation time, and significant uncertainties in the results. In this context, several types of calculation codes exist today: the so-called "shallow water" models are recognized as reliable for the representation of flows in 2 dimensions of space but are not used operationally at the scale of the agglomeration because of the long calculation times on real geometries. Indeed, in a metropolis such as Abidjan, the largest French-speaking city in West Africa, which will have 13 million inhabitants in 2050, compared to 4.7 million in 2014. In the context of flooding phenomena related to rapid and sometimes anarchic urbanization, with very strong contrasts in terms of land use and infrastructure, sometimes associated with a problem related to relief. Hydraulic modeling of the watercourses in these areas is therefore essential to deal with the problems related to flooding.

Hydraulic modeling is based on the resolution of the Saint-Venant equations in order to give values of water heights or flows in each mesh. In this framework, many models in two dimensions of space have been proposed and can be classified into two categories: 1) fine models, which are generally more accurate but require significant computation time and cost; and 2) large-scale models allow a considerable time saving, not only in terms of computation but also for the creation of the mesh. They are therefore fast enough to consider the production of real-time alerts compared to a fine model with a reasonable loss of information, although they are less accurate. The latter requires the estimation of new parameters related to topography and land use. Among these models are the porosity models, including the SW2D-DDP [3] water depth-dependent porosity model that was used in this work.

This dissertation employs different models of flow modeling by the fine mesh of the neighborhood and we have relied on the "classical" SW2D code developed at the laboratory HydroSciences Montpellier (HSM) to acquire more accurate results that accurately represent the flows generated in the urban area; this model was used to validate the SW2D model "with porosity," also developed at the laboratory HydroSciences Montpellier (HSM). In addition to the research work carried out in the framework of this thesis, flood mapping has been carried out for prediction.

1.2 Problem description

Floods are the most devastating natural menace to reach the majority of people in many urban areas around the world. Africa is one of the two continents in the world most affected by floods.

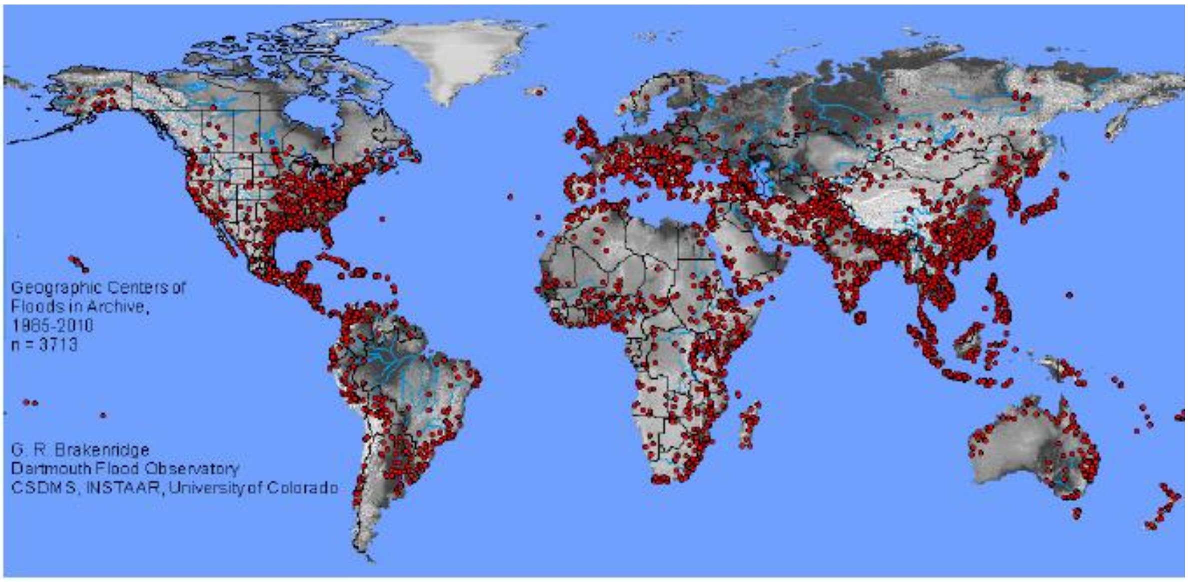

Figure 1 Geographic centre of inundations, 1985-2010

Floods are the most frequent disaster and remain a threat, especially in Sub-Saharan Africa (SSA)'s cities (Pusch et al., 2016; Tiepolo, 2014). Abidjan, the economic capital of Côte d'Ivoire, offers a prime example of this phenomenon of urban flooding. In that city, every rainy season is characterized by the number of deaths and the extent of their damage, mainly due to hydro-climatic events that occur during heavy rainfall. Uncontrolled urbanization generally leads to an increase in impervious surfaces, which limits the possibility of water infiltration into the soil and increases the volume of water runoff on the surface (Li et al., 2013). Additionally, urbanization is often accompanied by the artificialization of urban rivers, which further increases the risk of water overflows (Chocat, 1997; Douglas, 2017). Climate change, now significantly validated by the scientific community, is an aggravating circumstance. Certainly, increased frequencies and intensities of extreme rainfall events and rising sea levels will have a direct impact on the volume, intensity, and frequency of floods (IPCC, 2014). The IPCC report states with very high confidence that ecosystems and human's systems are significantly vulnerable to this.

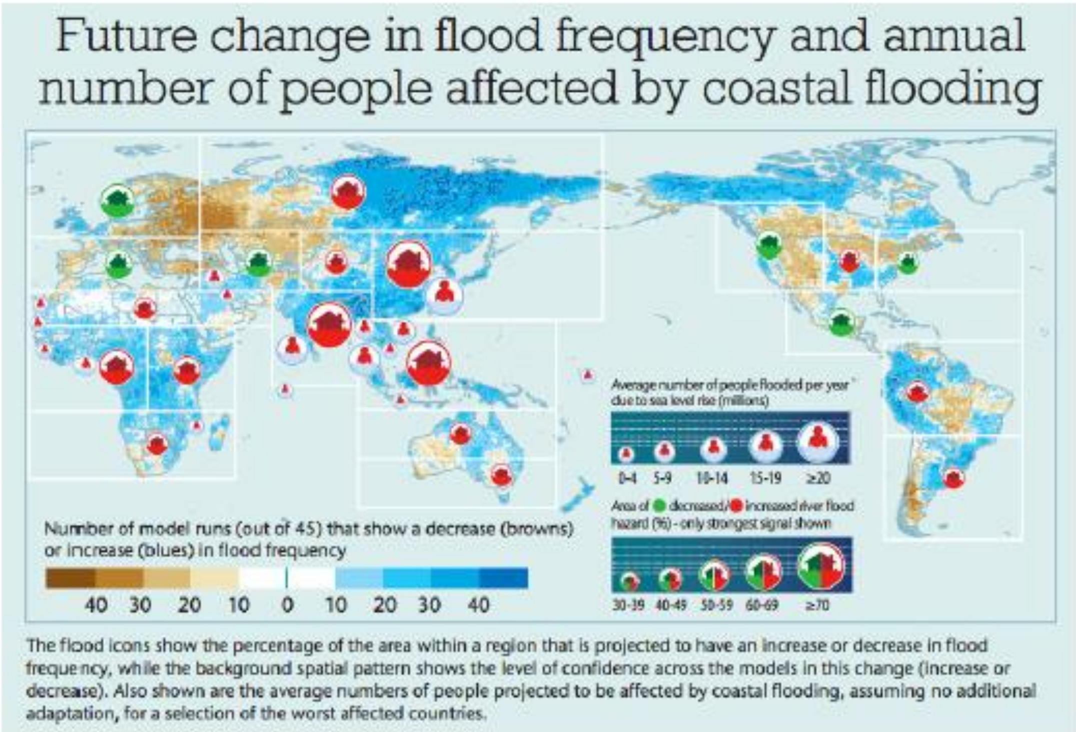

Figure 2: Future trends in flood frequency and number of people affected annually

The continent contains a population that is growing twice as fast as other regions in the world (Cohen, 2006). Beyond this high growth, management and planning remain a problem throughout the continent, particularly in the region south of the Sahara (Pelling et al., 2012; Silva, 2015). The absence or ineffectiveness of disaster management plans and the inadequacy of basic systems, infrastructures, and services contribute to the increasing vulnerability of urban areas (Jha et al., 2012). The inability to accommodate a fast-growing population in decent conditions explains why construction projects are located on unsuitable and dangerous sites, exposing cities to natural disasters (Pauleit, 2015), including floods. The deficiency of the drainage systems means a part of the population is affected by floods (Douglas, 2017). For three decades, Cote d'Ivoire, known as a country frequently affected by floods, with heavy rainfall, caused significant material damage and considerable loss of life, damage to infrastructure and property, and also the watercourses (river, lagoon), which came out of their beds, causing flooding of the riverside communities.

Each year, during the rainy season, the inhabitants of Riviera Palmeraie in Abidjan, which was chosen as the study site because of the paradox expressed by the fact that it is a high-social-status district (a prestigious district where most government officials reside) with a relatively large number of flood-affected people by rising sea levels.

Figure 3 Severe Floods Hit Abidjan Cote D'Ivoire Jun 2020

For example, we can mention the floods of June 18 to 19, 2018 in the district of Riviera Palmeraie, and especially the street called "Rue Ministre," which is littered with litter carried by the torrents that flowed over the weekend, which destroyed a lot of precarious houses along 03 to 05km. Still, in this same area, the water (flood water level elevated at 1.5m) has flooded the regularly built homes, carrying all their resident goods and food stuffs. Affected families were rendered homeless and have either relocated to host families or temporary sites like churches, schools, etc. While extreme weather continues, their current shelter solutions do not meet basic requirements, exposing children and the most vulnerable people to the risks of respiratory and waterborne diseases (DREF, 2018). Thus, practically all natural water sources are transformed into artificial canals, where the parts are often small enough to transport excess rainfall. This may have an effect on the balance of the system of water sources and may pose a risk to the ecosystem. In order to reduce exposure and vulnerability to floods, it is important to recognize all aspects related to flooding, including socioeconomic factors that explain why flood-prone zones keep attracting a part of the population.

CRCI search and rescue Team in Rue Ministre – Abidjan/19 June 2018 ©CRCI

Figure 4 Floods of 19 June 2020 in Rue Ministre of Abidjan

The perception of floods and mitigation actions by flood victims in the Sahel have been elucidated by Tschakert et al. (2010); Schlef, 2018). Soma et al. (2018), Tarhule (2005)). To strengthen the resilience of urban areas and minimize economic losses, it is necessary to develop participatory disaster management systems through community-based projects. Several structural and non-structural measures have been adopted by policymakers to minimize flood damage in urban areas. In Sahelian countries, for instance, since the 1950s, the majority of towns were built around watercourses without clear drainage systems or urbanization plans. Unfortunately, these measures seem to be ineffective (Okyere et al., 2013; Oumarou, 2017; Schlef et al., 2018). Given the occurrence of flood events in the study area, it becomes imperative to implement new approaches that should be able to better characterize flow discharges in urban areas and also fit into flood risk management strategies.

The most common modeling techniques currently used omit buildings and other obstacles in the potential flood zone, for the sake of simplification and lightening of computer calculations, but also because of the lack of georeferenced data for the structures. The high number of such structures in urban areas, as well as their proportion in relation to the size of the mesh, pose a representational challenge. However, having information about the flow in the streets of a city would be beneficial for the development of measures to reduce risks. The scale of predictions would then be local with information about the path, velocity, and depth of water as a function of time in the streets and at intersections. Thus, the important impact of floods, the future increase of extreme events, and the ageing of the infrastructure translate into a need for improvement in flood management in urban areas. The problem with this research topic is to set up a stable model, taking into account the representation of buildings whose output variables are as close as possible to the real observations.

The present study focuses on the realization of hydrodynamic modeling of the domain, which remains necessary to identify the zones of flood risk, their degree, and the water heights that can occur. These results can be useful in putting in place more judicious protection or compensation measures.

1.3 Objectives of the Study

1.3.1 Main objective

The overarching objective of the thesis is to develop a 2D hydraulic model for urban floods through hydrodynamic modeling in the urban areas of Abidjan city. Numerical simulations of flow are the primary tool employed in this study. The work will be based on fine 2D and porosity models.

1.3.2 Specific objectives

The detailed objectives of the present study are listed as follows:

- Creation of a fine mesh of the study area.
- Application of the "classic" SW2D model and analyses the simulation results.
- Realisation of coarser mesh and application of the "porosity" model SW2D-DDP and analysis the simulation results.
- Compare the differences in progress and results between the two models.

1.4 Research questions

In the context of urban flood effective modeling and with a view to proposing an effective 2D model, the following research questions can be divided into several sub-questions that arise and are tackled in this thesis:

- How accurately can a fine two-dimensional shallow water flow model be represented as a reference model?
- How much accuracy is gained by using a modified shallow-water model with porosity to represent the flow in the urbanized area?
- What type of model is required to be constructed for effective hydrodynamic modeling?
- What method of hydraulic model is preferable and what are the differences in the model results from modeling?

1.5 Scope of the Study

The purpose of this research is to describe the numerical flow model and to illustrate the typical open flow fields that the model is capable of simulating. Only urban building sites sewerage and drainage systems, and land cover maps are focused on in this research. Numerical models are developed for comparison with experimental results published. Model parameters are tested to determine the model sensitivity. This reduces the number of parameters to only those that have a major impact on the design. Model verification consists of comparing results computed using the two numerical models (fine and porosity). However, comparison results will focus on transient state flow and transitional regime. The results can be used to determine the appropriate parameters to be optimized in the future. Finally, the numerical will be applied to characterize the physical parameters that describe the flow, to examine the performance of the 2D hydraulic model for urban flooding, and to examine the applicability of the model as a design tool for improving surface flow modeling on the scale of an agglomeration in Abidjan, Cote d'Ivoire.

1.6 Significance of Research

For surface flow models on the scale of the agglomeration, the most challenging part is for several reasons: lack of knowledge of the geometry of the area to be modeled (building map, land use), lack of hydrological data to calibrate and validate the models. The complexity of the design of the mesh still requires prohibitive calculation times and strong uncertainties in the results. For the design of effective and economical urban drainage systems, it is important to estimate the design flows accurately. Many computer-based mathematical models have been developed to study catchment runoff (flows) in urban environments. These models may be used in different stages of the projects, such as screening, planning, design, and operation. Each stage may require a different model, although some models can be used for several of these stages. And through this prediction also, we can define easily the critical location within the existing channel so that improvement can be done quickly before flooding happens in that location. A lot of flow models used recently were not able to perform this task accurately.

However, there are still some flow models were developed to achieve especially effective and computationally affordable flood simulations in complex branched urban networks such as two-dimensional (2D) mode. There was some concern to the adequacy of a one-dimensional (1D) analysis of the flow conditions such as hydraulic variables which are commonly found in high-velocity channels. There was a question as to whether computing cross-sectional averaged flow variables provided a sufficiently accurate estimate of flow depths and velocities within these boundary features. Thus, a two-dimensional (2D) analysis was deemed necessary to evaluate these flow conditions which always cause overhead trouble in high-velocity channels.

A numerical model SW2D of free surface flows is used to predict flood hydrodynamics, especially in cases like branched urban networks, as well as to investigate urban flood flow controls in this thesis. Using a numerical model would accelerate this design process and lead to an improved initial physical model, thus reducing the time spent on the physical model. This would allow for the exploration of more design alternatives in a shorter length of time, resulting in a more cost-effective solution.

1.7 Synopsis of the thesis

This master's thesis is organized as follows: Chapter 1 starts with a brief introduction, problem description, and identification of key research questions to be addressed in this work. Chapter 2 presents a literature review on hydraulic models for urban floods at local and urban district scales using experimental and numerical approaches. Some shallow water models applied to urban flooding are presented, including 1D2D couplings and sub-grid methods like porosity function. Some sensitivity analysis is also presented, as well as the derivation of governing equations used in the model. In Chapter 3, the study area is examined and the background is described. The chapter ends with the details of the urban flooding event, as it is known. This chapter explains the initiation of the SMS software (Surface-water Modeling System) and the numerical application model based on the SW2D calculation code. The chapter is structured to mimic the first steps of the hydraulic modeling methodology (definition of purpose and requirements, collection of data). Afterwards, the contents are presented, including the choice of model, assumptions, processes, and their simplifications.

Chapter 4 will be discussing the model results obtained and a brief comparison between the two models, as well as the sensitivity analysis. Chapter 5 is a presentation of the main conclusions of the thesis that sums up the most important findings, proposes some possible recommendations, and outlines possibilities for further research.

1.8 Chronology and history of flooding phenomena in Côte d'Ivoire

The data cited in this section are all from André ALLA Della's (2012) article. In Côte d'Ivoire, the events of the last thirty years show that a certain number of natural phenomena are occurring more and more. Loss of human life and material and economic damage are relatively important due to these phenomena. Here are some of these events:

- Very violent tornadoes recorded in Abidjan and Adzopé between 1980 and 1990 caused significant damage to individual buildings or entire neighborhoods.

- In 1989, a flood of the Agnéby River inundated a whole part of the town of Agboville, causing significant material damage;
- Severe coastal erosion, particularly in Grand-Bassam, Grand-Lahou, Assinie and the Vridi-Port-Bout sector in Abidjan, causes considerable damage;
- Flooding in Grand-Bassam on multiple occasions as a result of the Comoé River's flooding;
- Landslides occurred on the Man-Biankouma axis at "Cote 120" in 1977 and 1988.
- In 1996, flooding in many areas of the city of Abidjan, landslides in Attécoubé and Gobelet, following torrential rains (more than 30 deaths and significant material damage);
- In 1998, a flood was followed by a landslide in the town of Abobo (5 deaths);
- 1998, flooding in some residential areas of Abidjan (material damage);
- The Bonoumin Riviera experienced severe flooding in 2002.
- In 2005 and 2007, deadly landslides in the town of Attécoubé
- Cocody was hit by deadly floods and landslides in 2008.
- In 2009, there were deadly landslides in Attécoubé and Gobelet; violent and devastating winds in Yopougon and Abobo;
- In the commune of Abobo, flooding occurs on a regular basis.
- In 2010 and 2011, there was widespread flooding throughout the city, as well as deadly landslides on the zoo road and in Attécoubé.
- The latest spectacular floods that covered almost the entire area of Abidjan caused the overflow of the dam on which this study is based.

The occurrence of such events indicates that some parts of the Ivorian territory are subject to risks of natural origin. Among these, urban areas are the most threatened, especially the city of Abidjan, which today has the highest human and economic concentration in the country: between 4 and 5 million inhabitants, or nearly 45% of city dwellers and 20% of the total population, which accounts for more than 60% of the country's economic activities. Urbanization in this area is so rapid due to Abidjan's triple administrative, political, and economic status that it is accompanied by a consumption of space unprecedented in the urban history of Cote d'Ivoire. For example, Abidjan has gone from 600 to nearly 60,000 hectares in less than 50 years (Haeringer, 2000 and AUA, 1993). As a result, urbanized areas are increasingly being declared outside of the original sites through the use of hazardous areas.
Basins, flood-prone valley bottoms, and especially slopes with little or no building potential.
Thus, in the current state of development of urban spaces, many Abidjanese live in areas where

They are more or less directly threatened by natural hazards that generate damage. Whatever these hazards are, each of them affects urban issues such as populations, housing, infrastructure, economic activities, and even the living environment. However, the impact of each hazard is not only a function of the type of land use and the level of development of the potentially threatened zones, but also of the capacity of the populations to react positively or negatively to a possible disaster. Given the importance of the human and economic stakes in the face of natural hazards in the city of Abidjan, it seems more than necessary to map the areas at risk, in order to determine the levels of vulnerability in view of the urgent actions to be taken. Indeed, if the exposed areas are not known and delimited, the risks will represent a greater threat to human life, the economy, and the living environment in this urban area, where the spatial distribution of the population and habitat does not always take into account the constraints of relief.

2 LITERATURE REVIEW

The work in this master's thesis focuses on urban flood modeling at the street and city scales. This chapter contains a comprehensive synthesis of research on urban floods, including numerical and experimental investigations, as well as sensitivity analysis. It starts with an overview of urban flooding before moving on to a basic discussion of the continental water cycle and the hydrological backdrop of urban flooding. The next sections cover hydraulic modeling, major hydrodynamic features involved in urban flood flows, and, in particular, "local" scale hydraulic crossings. The numerical methods commonly used for urban flood modeling are then discussed, including a review of works using various paradigms (1D, 2D, and 3D), as well as 2D and sub-grid scale methodologies. Sensitivity analysis (mainly variance-based global sensitivity analysis) is introduced, and its application in hydrology and hydrodynamics is also briefly reviewed. Finally, some problems are formulated.

2.1 Hydrology and process overview

In this section, we will look at some of the most important flood-related hydrologic processes. As reported by Mascarenhas et al. (2005), Figure *5* depicts the procedures that take place at various points during a city flooding event, as well as their relationships (2004).

Processes with a small to non-existent impact on the floods in Riviera Palmaraie have been removed from the diagram to maintain focus and clarity. As a result, subsurface processes other than infiltration, such as percolation and groundwater base-flow, have been dropped from the model. Furthermore, due to Abidjan's mild climate, snowmelt has been excluded. More climatic data may be found in section 3.3, and city floods will be covered in part of section 2.2.

Definitions

Precipitation

Precipitation refers to the liquid or stable section of aqueous particles that fall from the environment to the earth’s surface. It is also the amount of water that has fallen at a given point over time (American Meteorological Society, 2012).

Interception

Interception is "the system by means of which precipitation is caught and retained on vegetation or structures, which afterwards either reaches the floor as through fall or is evaporated." As a normal rule, this loss to runoff or circulated discharge solely takes place at the opening of the storm. " (American Meteorological Society, 2012).

Evapotranspiration

Evapotranspiration is the blended method of evaporation and transpiration through which

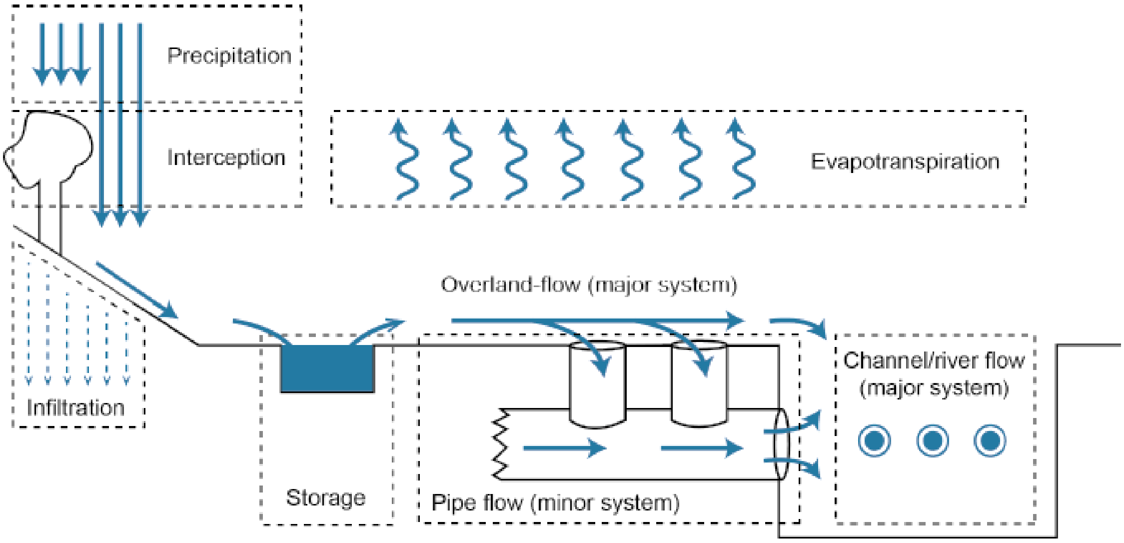

Figure 5 An overview of hydrologic processes during urban flooding. Groundwater flow has not been shown in the figure

The earth's surface is made up of open water and ice surfaces, bare soil, and vegetation (American Meteorological Society, 2012).

Infiltration

Infiltration is the manner in which precipitation or floor water passes through the soil surface into the lithosphere. Water that exceeds the infiltration ability produces both overland floats or ponding on the floor (American Meteorological Society, 2012; Seiler & Gat, 2007).

Storage

In particular, despair storage is the water that is retained in depressions in the surface of the ground. It ultimately infiltrates or evaporates (American Meteorological Society, 2012).

Overland-flow

Not all the rainfall is converted into overland flow. A section is lost due to interception, melancholy storage, infiltration, and evapotranspiration (Butler & Davies, 2000). The effective rainfall that is left, or in different phrases, the run-off that did not infiltrate, will become overland-flow and strike throughout the surface to the nearest entry factor into the sewerage system.

2.2 Overview on urban flooding

Urban flooding refers to the inundation of land or property in a more or less densely developed and populated region. Such hydrological events can be due to various combinations of hydrometeorological factors as presented above and also cite specific features such as topography, soil occupation and properties, and antecedent wetness. They can be categorized into different types according to where the water comes from and the generated processes. Coastal floods, river (or pluvial) flooding, floods caused by rising groundwater levels, flash floods, and urban flooding can all be distinguished. Climate drives and modulates urban floods, which are generally caused by precipitation, temperature, and the landscape (Shroder et al., 2015), overwhelming the infiltration capacity of an (urban) catchment, as well as the storage and conveyance capacities of drainage systems, such as storm sewers, as shown in figure 1. This study will concentrate on the urban flood that occurred in the Riviera Palmeraie region of Abidjan, which has had numerous flood episodes in the past year.Urban flooding refers to the inundation of land or property in a more or less densely developed and populated region. Such hydrological events can be due to various combinations of hydrometeorological factors as presented above and also cite specific features such as topography, soil occupation and properties, and antecedent wetness. They can be categorized into different types according to where the water comes from and the generated processes. Coastal floods, river (or pluvial) flooding, floods caused by rising groundwater levels, flash floods, and urban flooding can all be distinguished. Climate drives and modulates urban floods, which are generally caused by precipitation, temperature, and the landscape (Shroder et al., 2015), overwhelming the infiltration capacity of an (urban) catchment, as well as the storage and conveyance capacities of drainage systems, such as storm sewers, as shown in figure 1. This study will concentrate on the urban flood that occurred in the Riviera Palmeraie region of Abidjan, which has had numerous flood episodes in the past year.

Figure 6 Pictures of urban flooding during severe flood. Source: Online images of flooding in Riviera Palmeraie/Abidjan

frequently heavily inhabited and contain critical infrastructure. Furthermore, because of the change in flow from the sewer community to the city surface, toxic water might flood land and property (Jha et al., 2011). This is a one-of-a-kind problem for blended sewer systems, which increase foul flow.

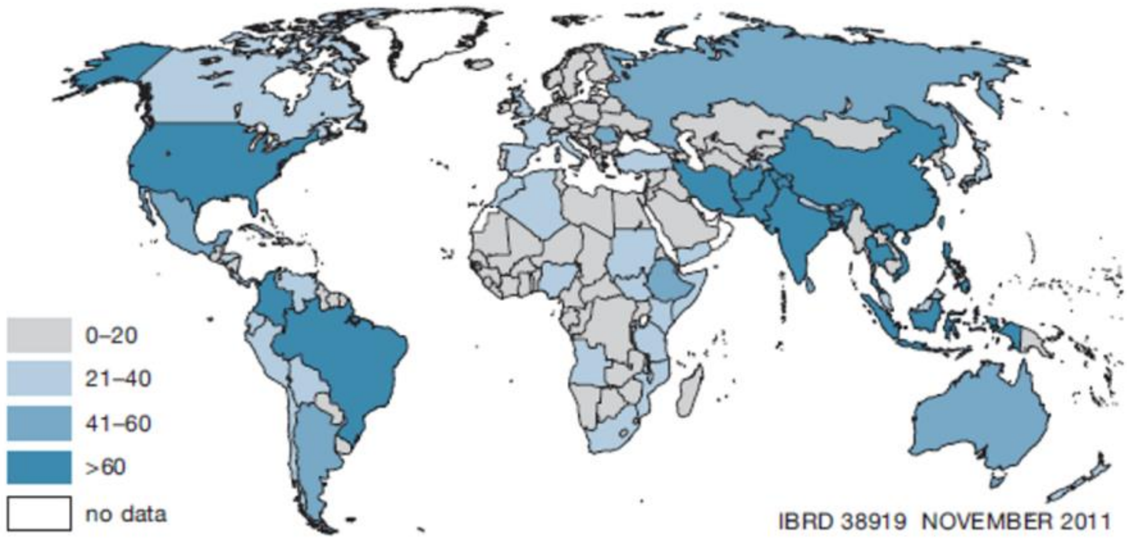

Figure 7 General Urban Flood Events, 1970-2011. Source: EM-DAT: The OFDA/CRED International Disaster Database www.emdat.be – Universite' Catholique de Louvain – Brussels, Belgium (Jha et al, 2011)

Each flood can generate one-of-a-kind types of damage, which may additionally encompass (Mark et al., 2004):

- Direct damage, commonly a cloth injury prompted by using water or flowing water;
- Indirect damage, such as site visitor disruption or manufacturing losses;
- Social consequences, such as psychological issues for inhabitants, as well as effects on fitness due to contact with flood water.

Ten Veldhuis (2011) developed two major measures for estimating flood damage. Tangible damages, which include all structural and infrastructure damage, and intangible damages, which include harm that is more difficult to quantify, such as anxiety, trauma, and inconvenience.

It is critical to establish a thorough estimate of the total damage caused by floods, which includes both tangible and intangible damages (Defra, 2004, Ohl and Tapsell, 2000, Fewtrell and Kay, 2008).

To estimate manageable harm and quantify threat, it is vital to understand how water strikes in the city environment. Consequently, a perception of the hydraulics of city flood flows is indispensable in order to apprehend and mitigate risk.

2.3 Urban water cycle and flooding

2.3.1 Urban water cycle

One of the most fundamental concepts in hydrology, and indeed in water resource management, is the hydrologic cycle (also referred to as the water cycle). The great water cycle, driven by the thermal energy of the sun, describes the fluxes of water within the so-called hydrosphere on earth, including oceans and continents. For roughly 4 billion years, the amount of water on Earth (approximately 1,386,000,000 km3) has remained nearly constant (https://water.usgs.gov/edu/earthhowmuch.html, access on April 3, 2018), whereas its partitioning into the oceans, atmosphere, cryosphere, and continental surface and underground water is time and space dependent. The continental water cycle, also known as the hydrological cycle, describes the movement of water on, above, and below continental surfaces as illustrated in Figure 8. Hydrology is the scientific field, as a consequence of meteorology and fluid

mechanics, focused on the continental water cycle. The main physical processes involved in water repartition are evaporation, condensation, precipitation, infiltration, surface runoff, subsurface flow, and groundwater flow. These vertical and lateral hydrometeorological processes are nonlinear and coupled, characterized by various relaxation times. Evaporation,

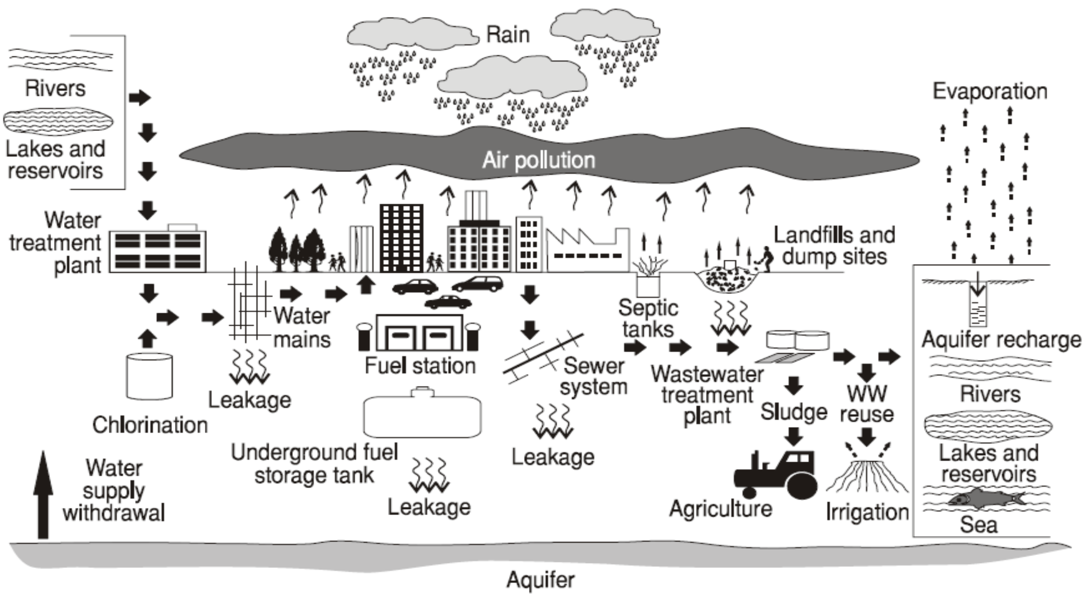

Figure 8 Schematic of urban water cycle by the International Hydrological Program (IHP)

flow processes along with the variability of the forcing. Improved understanding and predictive performance of models of those hydrological processes at various spatial and temporal scales is of particular interest for:

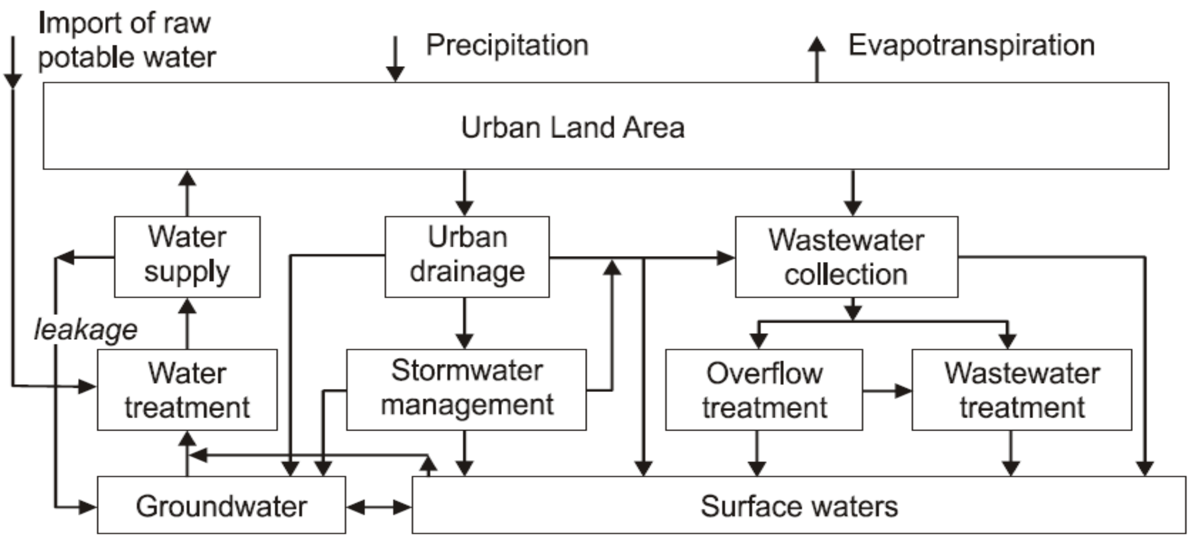

Figure 9 Urban water cycle with their main components and pathways

- Advancing our understanding of the Earth's water cycle and completing it in terms of quantitative water balance between the ocean, continents, atmosphere, and cryosphere
- In the context of climate change, developing sustainable water management and engineering techniques (Pachauri et al., 2014).

Water management includes many problems involving different spatio-temporal scales. Hydrological extremes, such as floods, may occur at short time scales and their predictability represents an important challenge. Indeed, weather-related disasters seem to become increasingly frequent, especially storm-floods, which represent 47% of all weather-related disasters worldwide over the period 1995–2015 (Pachauri et al. (2014); Wahlstrom and Guha-Sapir (2015)).

Depending on storm and catchment properties, various flood types can occur, as detailed in the following section.

2.3.2 The impacts of urbanization on the water cycle

This reintegration of the river into the city aims to limit the harmful consequences of urbanization on the water cycle but does not eliminate them. Human, industrial, and urban settlements and activities modify the flows between the different compartments of the water cycle. They intervene both in the quantities available for the flow and in the flow paths. Two determinants of runoff are sensitive to human action: soil permeability and vegetation cover density. However, one of the most visible consequences of cities is the waterproofing of the soil, which then severely limits the possibilities of water infiltration. In France, the waterproofed surface increased tenfold between 1955 and 1965 (Eurydice 92, 1991). As the soils are waterproofed, water can no longer infiltrate and runoff, leading to accumulations in the troughs and flooding and the non-recharge of groundwater. Furthermore, runoff collects all of the pollution resulting from various discharges: urban, industrial, and so on. In addition, urbanization is always accompanied by the establishment of a network of roads and streets, sometimes built at an elevation compared to natural land or, on the contrary, in trenches. In both cases, this network can significantly alter the flow of surface water in the plain during river overflows.

The second direct consequence of urbanization is an increase in flow rates, leading to an increase in peak flows. This increase in flow rates is due, in urban areas, to the replacement of a natural hydrographic network, sometimes non-permanent, using winding paths, very crowded but not very steep, by a very different sewerage network (steep, straight...). This underground path is often coupled with reprofiling of watercourses (sizing, riprap, or even concreting of the banks...), which also increases the flow speed. To reduce this risk, it is preferable to the construction of new urban districts.

Urbanization leads to a local change in hydrological functioning, but it can also have downstream repercussions and, more generally, a change in the initial state of the watershed.

Table 1 Classifications and examples of impacts

Type of Impact	Environmental Compartment					
	Atmosphere	Surface Waters	Wetlands	Soil	Ground-water	Biota
Physical	Heat island, increased precipitation downwind, dry deposition	Increased surface runoff and flooding, higher water temperature	Changes in water balance	Increased erosion, changes in physical structure	Lower or higher water table	Loss of habitat, benthic organism burial

2.4 Stormwater runoff

Changes to the runoff regime represent one of the most significant impacts of urbanization. Urbanization affects surface runoff in three ways:

→ increased runoff volumes as a result of decreased rainwater infiltration and evapotranspiration.

→ increasing the speed of runoff due to hydraulic improvements in conveyance channels;

→ The peak discharge is caused by reducing the catchment response time and thereby increasing the maximum rainfall intensity. Thus, urbanization changes the catchment hydrologic regimen. In general, the magnitude of such increases depends on the frequency of storms, local climate and catchment physiographic conditions (soils, degree of imperviousness, etc.), as partly illustrated in Figure 10. Figure 11 shows two runoff hydrographs from the same catchment before and after urban development. The figure demonstrates changes in the runoff hydrograph caused by urbanization and can be controlled by storage. Note that the storage element (see section 2.5) reduces the peak, but not the volume of runoff, which contributes to increased runoff flows over extended time periods.

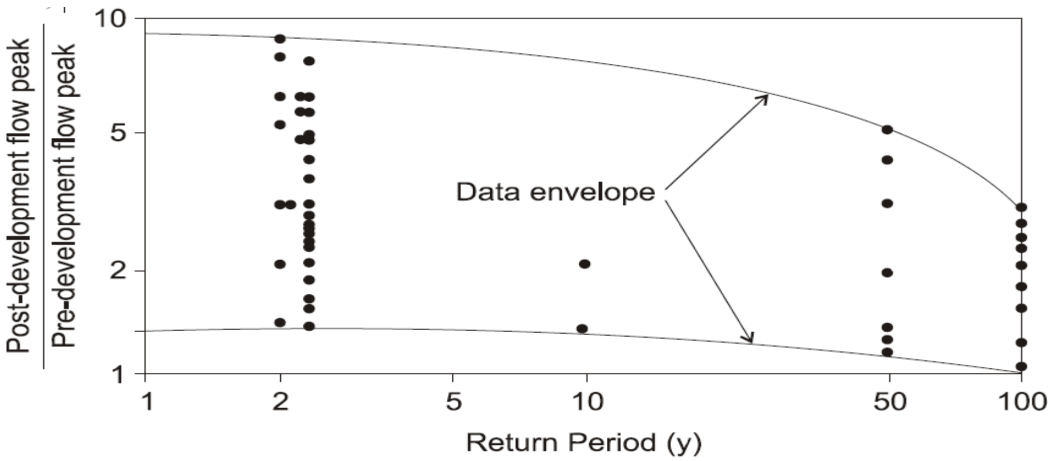

Figure 10 Effects of watershed development on flood peaks taken from (Marsalek, 1980)

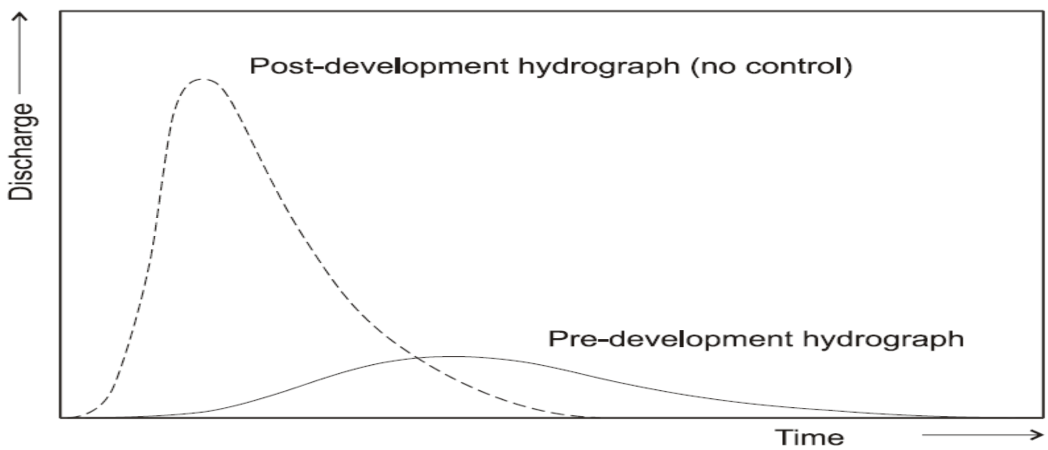

Figure 11 Runoff hydrograph before and after urbanization

2.5 Stockage elements

A distinction can be made between those that provide permanent storage and those that provide temporary storage. The elements of definitive storage, which permanently remove a certain quantity of water from the flood, are mostly artificial. They correspond to all the usually viable spaces located underground (parking lots, residential basements, underground crossings, subways, etc.) or in surface depressions of various origins (earthworks, banco quarries in African cities, etc.). Temporary storage elements are numerous; some have been created precisely to store part of the runoff in order to delay the arrival in the network of contributions from certain surfaces. These structures are becoming more and more numerous with the advent of so-called alternative sanitation techniques (Chuzeville 1992; Azzout 1994). Drainage elements as well as permeable obstacles are also potential storage elements.

2.6 The analysis of the hazard

By its definition, the scientific study of the hazard is made on the basis of probabilities and is therefore based on its frequency and magnitude. Its characterization depends strongly on the methods of measurement. The statistical study of hazard seeks to establish the likelihood of causality from the observed physical manifestations of the phenomenon. The characterization of hazard depends on three fundamental parameters:

- The geographical boundaries within which the hazard may exist.
- The magnitude of the effect, its maximum energy factor;
- The frequency of the phenomenon determines the period of time in which it is likely to occur.

2.6.1 The hazard inundation

In the case of floods, the hazard corresponds to the conditions of submersion, that is to say, a covering of water that overflows or flows into a territory. It is available according to parameters such as water height, flow velocity, submersion duration, frequency or period of return, seasonality, and can be developed in the form of scenarios (training methods, propagation conditions, locations of overflows) ... The probability of occurrence of a flood, i.e., its return period, is an essential piece of data but highly dependent on the periods of measurement of the phenomenon.

2.6.2 Flood types

2.6.2.1 General classification

A flood is a natural hazard that can occur in many places worldwide due to the combination of several factors that can include: precipitation, soil (and/or underground networks) saturation, ocean storm surge, dam/breach breaking, debris-choked rivers. It is commonly defined as the overflow of water over land and built-up areas that are usually dry. Flooding can be classified into at least 4 types (Dauge, 1999; Ledoux, 2006) as follows:

- ✓ Flooding by overflowing rivers (slow and fast-onset floods);
- ✓ Flooding by runoff (in urban or rural areas);
- ✓ Flooding by rising water tables;
- ✓ Marine flooding (marine surge).

Another classification is to distinguish between slow kinetic floods (lowland flooding and upwelling) and rapid kinetic floods (torrential floods, runoff). However, these classifications do not express the full diversity of floods, which take on a specific aspect according to local factors. Indeed, a flood is often the result of a combination of factors (upwelling, urban runoff, and overflow). In the context of this thesis, because of our study grounds, the types of floods present are listed below:

→ Floodplain

They result from long-term rainfall over large watersheds with a little rugged terrain. In this type of configuration, the water gradually rises, and the stream exits its minor bed to occupy part of its major bed. The flood is characterized by a slow rise in water levels (greater than 24 hours). According to the Ministry of the Environment in the "Program for the Prevention of Floods Linked to Urban Storm Runoff and torrential Floods" (1994), "The criterion defining a lowland flood is linked to the time of rise of the flood. A flood will be "reputed" plain if its rise time allows an effective intervention before the maximum of the flood (> 12 h). The decrease is also slow, and the duration of submersion can then last several weeks. Of course, lowland flooding can have various specific aspects depending on the type of river, its development, and local configurations that can cause more brutal rises. The magnitude of flooding can be aggravated when the stream simultaneously receives flooding from several of its tributaries, especially if rain moves along the hydrographic axis during the flood. In this type of flood, the hazard is measured by the height of submersion and by the duration...

→ Flash floods

They are observed in the presence of small watersheds or in climatic and topographical contexts favoring rapid flows. Floods with a sudden and often difficult-to-predict appearance, a short rise time, and a relatively large specific flow. These flash floods are therefore generally linked to intense rain events and often manifest themselves in basins of moderate size "(IAHS-

UNESCO-WMO, 1974). Since a large amount of water flows towards the watercourse, the rise of the waters is very rapid. We speak of "flash floods" for basins of less than 500 km2 and rapid floods for basins of larger size. Thus, for Roche (1992), "torrential floods are characterized at first approach by the speed of the response of the watercourse (flash flood): generally, less than 6 hours"; and the Dauge report (1999) speaks of a concentration time of less than 12 hours for rapid floods. These phenomena are present in regions prone to very high intensity rainfall and/or rugged relief (Mediterranean, mountainous, tropical...). In these cases, it is common to observe "waves" of flooding, and the hazard is characterized essentially by the speed of flow and not the duration of submersion. For these episodes, the decrease is just as rapid when the rainfall stops. In the two cases above (slow floods and rapid floods), in addition to the climatic factor, the influence of the watershed is predominant. The reaction of a watershed subjected to a particular rainy period is characterized by its rate of rise and intensity. These two characteristics are a function of the type and intensity of precipitation and various morphological characteristics of the basin that define its "time of concentration." The size of the basin, its shape, elevation, slope, and orientation (Musy, 2005) are the first factors to be taken into account. Then come the type of soil, the vegetation cover, the characteristics of the hydrographic network and the anthropogenic development it has undergone (type of urbanization, agriculture, development...). In the same watershed, depending on climatic events and/or the characteristics of the sub-basins, both types of flooding can therefore occur. This is particularly the case in Brittany where, during the floods of 2000-2001, if the majority of the floods were linked to slow lowland floods, it was observed that local floods had faster kinetics (Huet, 2001).

→ Marine floods (marine surge)

In coastal areas, and particularly in estuaries, floods can be influenced (or even caused) by marine overcoats linked to tides, storms, and swells. In addition, the conjunction of high tides simultaneously with a large river flow leads to flooding or a worsening of these. These three types of flooding will be addressed in the territories studied in this thesis. Other flood phenomena are also present locally. These include:

→ Flooding by urban runoff and network overflow

Waterproofing of the soil (buildings, roads, car parks, etc.) limits the infiltration of rain and accentuates runoff, which often causes saturation and backflow of the rainwater recovery network. This results in varying degrees of rapid and rapid runoff on the streets (Scarwell and

Laganier, 2004). This trend towards soil sealing tends to increase with the urbanization of the territory.

→ Flooding by rising water tables

When the soil is saturated with water, it happens that the water table outcrops. This phenomenon particularly affects low or poorly drained land or areas with aquifers close to the surface. (Source: Prim.net, 11/06/2009). Flooding is very slow, often resulting in a long submersion. Excessive recharge of groundwater comes from a surplus present over several months or even several years (Dupont et al., 2008a). There can be a very long period of time between the triggering rainfall phenomenon and the discovery of flooding. Indeed, flooding can occur several months after excess rainfall, as was the case in the Somme in 2001.

2.7 Physical processes involved in urban hydrology

Urban hydrology is the science of investigating the hydrological cycle (see Figure 13) and its changes, water regime, and quality within the urbanized landscape and its impacted zones. The hydrological process in urbanized catchments consists of (Fletcher et al. (2013); Salvadore et al. (2015)):

Figure 12 Pictures of urban flooding during severe flood

Meteorological forcing: the accurate prediction of rainfall-runoff interaction highly depends on rainfall measurement over an urban area and its upstream catchment (e.g. with meteorological radars or new techniques based on cell phone networks, for example), rainfall forecasting and rainfall modelling (Skamarock et al. (2005); Seity et al. (2011)). Surface runoff process:

urbanization is accompanied by the replacement of natural or cultivated soil with impervious surfaces, which has profound impacts on urban hydrology. The volume of surface runoff can increase dramatically due to impervious surfaces where infiltration is impossible, hence water storage is impossible. Subsurface flow processes: subsurface flows in urban sewers and water supply networks, underground networks (Ishigaki et al. (2003); Noh et al. (2016)). The accumulation of overland flow in urban areas is caused by surplus rainfall in areas with imperious surfaces and inappropriately designed drainage systems, which can be the main reasons for urban flooding.

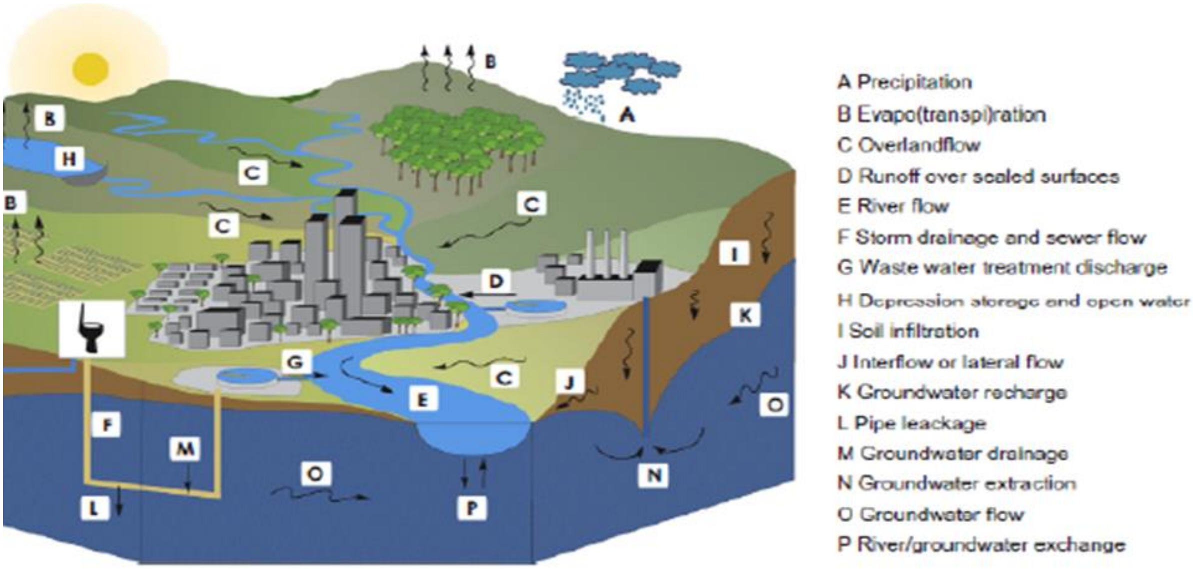

Figure 13 Hydrological processes about physical phenomena involved in an urbanized catchment taken from Salvadore et al. (2015)

2.8 Urban flood flows physics and risk to people

The increase in flood damage is particularly marked in urbanized areas, which represent an increasing percentage of the world population. Both increasing urbanization and the potential rise of high-to-extreme rainfall events should lead to more frequent urban flooding. In urban areas, flood effects can be exacerbated by existing paved streets and roads, which increase the speed of flowing water. The flood flow in urbanized areas constitutes a hazard to both the population and infrastructure. Important features of this hazard are the variability of water depth and velocities (Mignot et al. (2006); Yu and Lane (2006)). In urban areas, flood flow paths are quite complex and related to the topology of the city. From a hydraulic point of view, the structure of the city formed of building blocks is organized on the basis of networks (Paquier et al. (2015)): the hydrographic network, including the rivers, underground sewer network, and street networks (Finaud-Guyot et al. (2018)). During urban flooding, the streets can become the main flow paths while remaining the only means for emergency services and evacuation of the population. The hydrodynamics of urban flood flows can be viewed at two different scales of interest:

- Local scale: the study focuses on the flow properties (velocity and cross section/submersion depths) at a local scale in a section of a street or at a crossroad with confluences or difluences.
- District/city scale: the studied domain is composed of several streets and crossroads, hence forming a branching network.

Therefore, it is of paramount importance to improve risk assessment based on flow physics and prediction tools that are efficient both at the local and city scale. A bibliography of hydrodynamic models and hydraulic modeling is presented in the next section, followed by a synthesis of flow studies at the district and city scales.

2.9 Hydrodynamic models

One-dimensional (1D) and two-dimensional (2D) models are used and have been validated to have the capacity to simulate inundation patterns, water depth, and speed for rivers and floodplains (Bates and Roo, 2000; Horritt and Bates, 2002; Hunter et al., 2005; Mason et al., 2003). One-dimensional models are successful at simulating actual flooding phenomena in channels, but they are incapable of representing spatially complicated drift patterns and topography where overbank flows manifest (Mason et al., 2003). More recently, 2D finite distinction and finite models have been developed to simulate floodplain inundation patterns and the floodplain bodily processes. Studies exhibit that the 2D modeling method is successful in simulating river floodplain bodily procedures in complicated topographies (Horritt, 2000; Horritt and Bates, 2002; MacWilliams et al., 2004). The 2D model is additionally in a position to simulate neighborhood velocities, floodplain inundation depths, durations, and shear stresses, which are all essential parameters that force riverine ecological procedures and are an indicator of flood hazard in city settings.

2.10 hydraulic modeling

The hydraulic model calculates flood levels and flow patterns and also simulates the complex effects of backwater, overtopping of embankments, waterway confluences, bridge constrictions, and other hydraulic structure behavior (Néelz and Pender, 2007). The calculations are based on mass and momentum conservation. Hydraulic models are more accurate but also more expensive than hydrological models. The complicated nature of the floodplain flow patterns and the importance of obtaining community confidence in the process require that state-of-the-art modelling techniques be adopted (Bates et al., 2005; Horritt and Bates, 2002).

Hydraulic modeling is described by Maniyar et al. (2015) as a concept integrated to perform flood routing for computing peak flow attenuation and to map the depth of the flood zone. Chidinma Blessing has also expressed himself in other papers. Okoye et al. highlighted the developed hydraulic modeling tools such as Geographic Information System (GIS) software, geologically referenced information, and the HEC-RAS (Hydrological Engineering Center's River Analysis System) by the US Army Corps of Engineers in 2015 as software used in the flooded zone that can be identified upon a topographic map such that the vulnerable area can be easily identified. In hydraulic modeling, one of the most important aspects is the topography of river canals and flood plains, which can affect both flood dynamics and the extent of the simulated flood (Nicholas and Walling, 1997; Bates et al., 2020). Eleutério (2013) has also shown that the low relief of the floodplains indicates that errors in the hydraulic results can lead to broad differences in the delineation of the flooded region. According to Nguyen et al. (2021), hydraulic modeling was used to create a hazard chart, which was combined with exposure and vulnerability data to produce a detailed flood risk map. Hydraulic models are used to examine potential urban flood threats with a view to reducing them under various vulnerabilities and exposure scenarios. Regardless, Arrighi et al. (2013) illustrate that the hydraulic model is adopted, with several advantages in terms of ease of application, and can also measure with high accuracy the flood depth in urban areas alongside a high resolution and up-to-date Digital Surface Model (DSM). The capacity of the parsimonious hydraulic model used to describe the pattern of flood depths in similar situations is estimated by comparison with the marble-plate record of the historic city floods. In addition, Arrighi argued that hydraulic modeling is a method that has made it possible to assess the efficiency of hydraulic structures (e.g., dams and canals or drainage). Moreover, Casas et al. (2006) highlighted that the potential effects of the errors on risk assessment, flood control, and flood hazard classification underscore the significance of improving the quality of topographic data. The use of digital terrain models (DTMs) for hydraulic modeling is currently constrained by their availability or by economic factors.

In recent years, research has been conducted to address these numerical issues. For example, Xia et al. (2017) developed methods to maintain numerical stability and accuracy in order to develop a numerical scheme for modeling overland flows over complex bed terrains. Unlike natural catchments, urban areas have complex topographic features and underground infrastructure that have a significant impact on urban flooding. Some studies developed a porosity-based SWE model to generalize the effects of dense urban buildings (Sanders et al., 2008; Kim et al., 2015; Guinot et al., 2017; Bruwier et al., 2017). Bruwier et al. (2017) suggested a method for determining the porosity characteristics that reflect the various obstacles' distinctive sizes. This method can obtain speed-up values between 10 and 100 while the errors in water depths remain low. The majority of the research into porosity-based models focuses on numerical approaches for handling urban flood dynamics caused by upstream inflows rather than direct rainfall. Few large-scale applications of rainfall-driven surface water floods have been investigated. Furthermore, comprehensive urban flood models with complex urban surface buildings and subterranean drainage systems have recently been built. For example, Glenis et al. (2018), for example, provided a complete 2D SWE-based model that comprises not only a pipe flow module but also representative buildings and urban infrastructure based on high-resolution DEM.

3 METHODOLOGY

3.1 Introduction

To delimit the flooded areas, recent investigations by scientists (Horritt et Bates, 2002; Noman et al., 2001; Patro et al., 2009; Sarhadi et al., 2012) show that current approaches are based on hydraulic modeling intersecting pre-selected water levels with a flood plain surface. In fact, hydraulic simulation aims to investigate the propagation of flood waves in a river, delineate flood plains, and simulate water levels. Numerical approaches can be conducted with one-dimensional or two-dimensional models of the water surface (Horritt and Bates, 2002; Nardi et al., 2006; Sarhadi et al., 2012). Hydraulic models are mathematical tools that try to replicate fluid movement and, in most circumstances, involve parameter estimation. Based on their spatial representation of the flood plain deficit, the models can be classified in a dimensional manner (Teng et al., 2017). The purpose of this work is to develop the two-dimensional surface flow solved by shallow water models with porosity more adaptable to explain the flow under shallow water conditions for conservation laws of mass and momentum fluid particles, equations to solve by representing flows in Cartesian (x, y) directions. Porosity may thus be used to describe the fact that Riviera Palmeraie, which is one of Abidjan's headquarters vulnerable to flooding, is mostly a small portion of the total surface area. The application of this method is generally done in complex geometries such as those seen in urban areas. Generally, in every hydraulic model, data collection and tools are necessary for the development of the models present in the specific modeling approaches for flood risk.

3.2 Current conditions of the Study area

3.2.1 Location

The site of the Riviera Palmeraie is part of the chicest and most luxurious districts of the town of Cocody, and it is characterized by its beautiful landscape. Cocody is one of the 10 communes of Abidjan, located on the eastern side of the city of Abidjan between latitudes 5°19’ and 5°27’ N, and longitudes 3°54’ and 4°1’ W, and is the second largest district of Abidjan after Yopougon. According to the 2014 national census, its population is 447,000 (10.17% of Abidjan’s population) with an area of 144.59 km2. The Riviera Palmeraie is located in the town of Cocody on the Cocody-Bingerville axis. It is located more precisely in the center-west of Cocody and is limited to the west by the district of Bonoumin, to the north by Angré Caféier and Djorogobité, to the southeast by the Commando Camp of Akouedo, and to the south by the Riviera 3. The study area is one of the communes that knows some flood incidents, with the last data recorded after the flood of June 20, 2020.

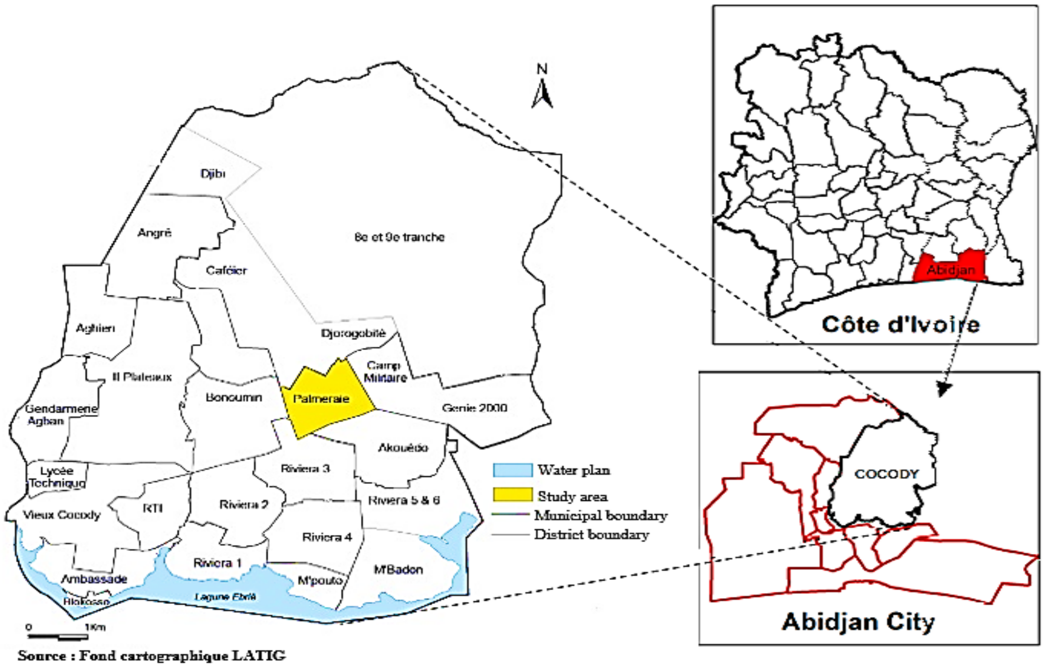

Figure 14 Location of the Riviera Palmeraie in Abidjan/Côte d'Ivoire

Riviera Palmeraie covers an area of approximately 0.54 km2. The study area consists mainly of residential neighborhoods (Palmeraie, Riviera, Djorogoité, SCI Rosier) recognized for the quality of their architecture and inhabited by the wealthiest Ivorian social class. This area is known for the recurrence of extreme rainfall events, and to remedy this problem, several facilities have been put in place to tackle the problem.

3.2.2 Climatic characteristics

3.2.2.1 Climate

From a climatic point of view, Côte d'Ivoire is crossed by the movements of two important air masses: an air mass coming from the north, characterized by a dry and hot wind from December to January, the harmattan, and a mass of air coming from the south-west, the Atlantic Ocean, consisting of humid air. The contact of these two air masses forms the Inter-Tropical Front (FIT), which causes monsoon-type precipitation. The seasonal movements of fit over Côte d'Ivoire make it possible to distinguish four main climatic zones characterized by a variable rate and volume of precipitation. Among the four climatic regions (South, Centre, North and Central West), the South is characterized by a transitional equatorial climate with two rainy seasons (April–July and October–November) alternating with two dry seasons (December–March and August–September).

These seasons are clearly differentiated by the rainfall regime:

- the great dry season, from December to March, is characterized by very cloudy and foggy skies in the morning, clear and sunny the rest of the day. Rainfall is rare;
- the great rainy season, from April to July, is characterized by very strong cloudiness, rains
- the small dry season, from August to September, is characterized by short-term insolation; the number of rainy days is high with low intensities;
- the short rainy season, from October to November, characterized by significant insolation.

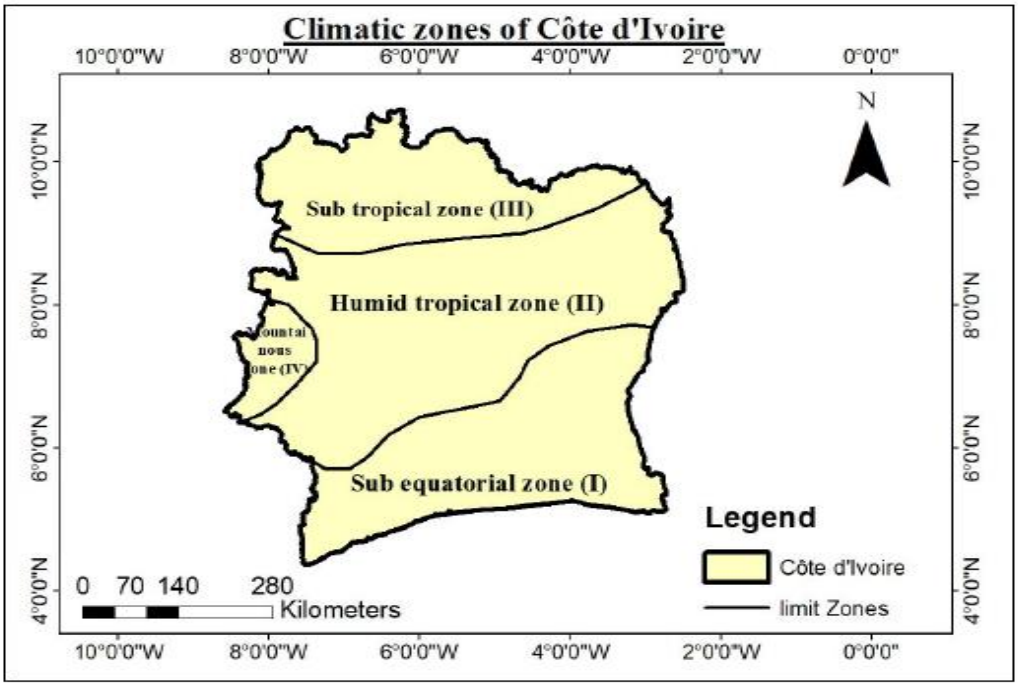

Figure 15 Climate zones of Côte d'Ivoire (Goula et al, 2006)

3.2.2.2 Rainfall

Rainfall in Cocody also varies throughout the year with two peaks. The first peak is reached in June during the long rainy season with a total monthly precipitation of approximately 550 mm. The second peak is reached in October with a total monthly precipitation of 150 mm. In fact, rainfalls in this region of Africa occur with the advent of the West African Monsoon, which is governed by the air flow of the Intertropical Convergent Zone (ITCZ) according to Lucio et al; Sultan et al.

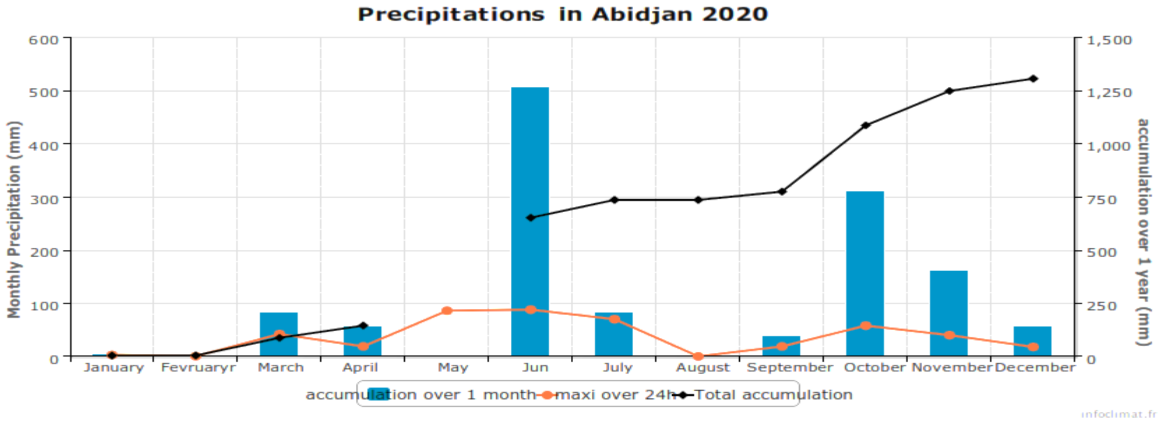

Figure 16 Rainfall precipitation variation in Abidjan city

3.3 Topography

The Riviera Palmeraie is located on a high plateau relief upstream and relatively flat downstream. This relief is inclined from north to south and presents slopes that vary from 19 to 62m and valleys as shown on the topographic map of the site.

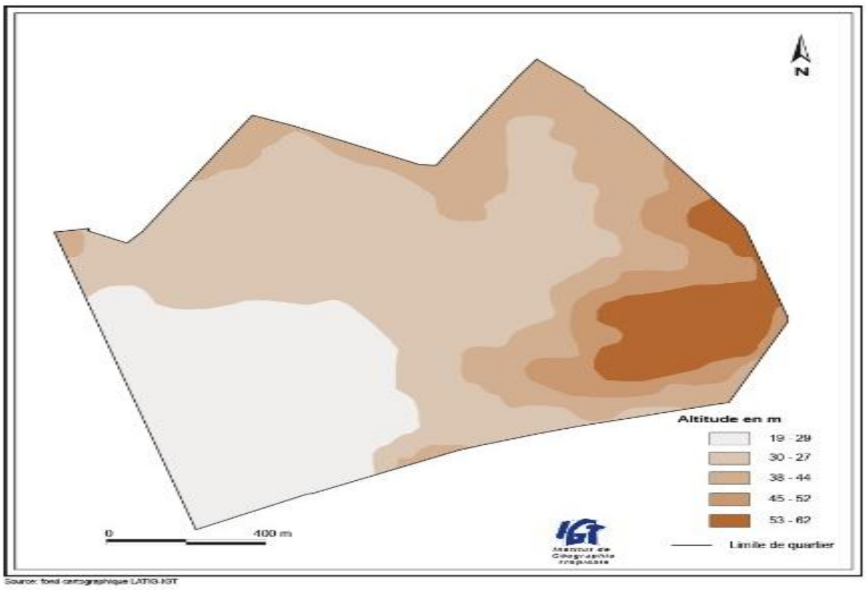

Figure 17 Topography of the Riviera Palmeraie

3.4 Relief and geomorphology

The District of Cocody in the Abidjan city, in which our area of study is, presents globally a little contrasted and monotonous relief. Indeed, the geomorphology of the municipality of Cocody is on a large plateau. This relief is separated from the municipalities of Adjamé and Plateau by a large neckline which starts in the south of Abobo and ends at the bay of Cocody. With an average altitude around 40-50 m, it has a north – south flow direction. Indeed, altitudes vary between 80 and 100 m in the north and between 20 and 30 m in the south. This plateau ends on the Ebrié lagoon but the transition is a cliff on the side of the neighborhood of Cocody. This cliff is detached from the Lagoonal costal line at Riviera where it behaves like a real bank from, separating the plateau from a small plain of 2 to 9 m. With a west-east direction, this bank, just like the cliff, is made of a series of valleys. These valleys and their tributaries are used as natural channels for the drainage of stormwater of the municipality of Cocody (Alla Della, 2015).

3.4.1 Morphology and typology of urban area

The urban morphology and its typology can have consequences on the "construction" of the city. Thus, the location of buildings can create a different vulnerability in the event of flooding. In addition to the formal diversity, to know the city, there is the art of recognizing its characteristic elements and the way in which they organize themselves among themselves. Urban morphology is therefore a way to "read the city", in order to explain its form or to distinguish the forms of its different components. In this sense, it is very closely linked to the notion of typology. Typology is a method for recognizing elementary objects or components of the same type. The typology of the building is a function of the form and the constructive mode of the latter (collective, individual, continuous...). The criteria used by urban planners or architects to carry out this reading of the city integrate historical, social and economic aspects. They often relate the functions of buildings to their shape, complementing their study of the city with a functional analysis. Thus, Rossi (1981) considers that the function of a component of the city may be different in the same form, because the function may evolve and the form may persist. On the other hand, Hillier (Merlin and Choay, 1988) is only interested in the physical and spatial form of the city when he evokes morphology. According to him, what matters is the geometric description of the space and the built forms and the links between the two. Indeed, the study updating the Abidjan Master Plan (1996) defines eight types of habitat that are grouped into four main groups: precarious housing, housing on courtyard, individual housing all standings combined and collective housing all standings combined. The characteristics of these different types of habitats are defined in the table Table 2 below:

Table 2 Type of housing in the Abidjan city

Four groups of housing	Eight types of housing	Characteristics
Spontaneous housing	Precarious housing	It is defined as a housing complex built without title deed
Progressive housing	Common courtyard housing	It is a set of constructions built around a common courtyard. Is mostly like the village type.
	Collective housing of medium standing	These are constructions in strips or in height, made by the state or by private individuals.
Economic housing	Collective housing of medium standing	These are constructions in strips or in height, made by the state or by individuals.
	Good quality collective housing	It also corresponds to affordable housing. These are residences of good standing.
	Economic individual housing	It is a set of individual houses of sufficient economic standing, built by the state or by individuals. This habitat also corresponds to the economic habitat.
Residential housing	Individual medium housing	These are individual constructions on small and medium-sized plots of medium standing.
	Individual nice housing	These are individual dwellings on large plots of high standing. This habitat is accessible only to the better-off social class.

3.5 Geology and Soil

The geology of flood-risk areas is a criterion to be taken into account, as it can amplify or mitigate the magnitude of flooding. Generally, permeable formations promote water infiltration. In addition, impermeable or low-permeable rocks, such as crystalline rocks, promote surface runoff. Areas containing crystalline rocks can also significantly affect the generation of flash floods (Bonacci et al., 2006). Therefore, crystalline rocks as well as lake deposits (clays, marls). Alluvial and continental deposits were rated lower because of their greater infiltration capacity.

The geological context of Abidjan is that the Côte d'Ivoire sedimentary basin is 350 kilometers long from east to west and has a very narrow north-south width of 10 to 40 kilometers. The successive layers are in a monocline position and the dip is in the direction of the ocean.

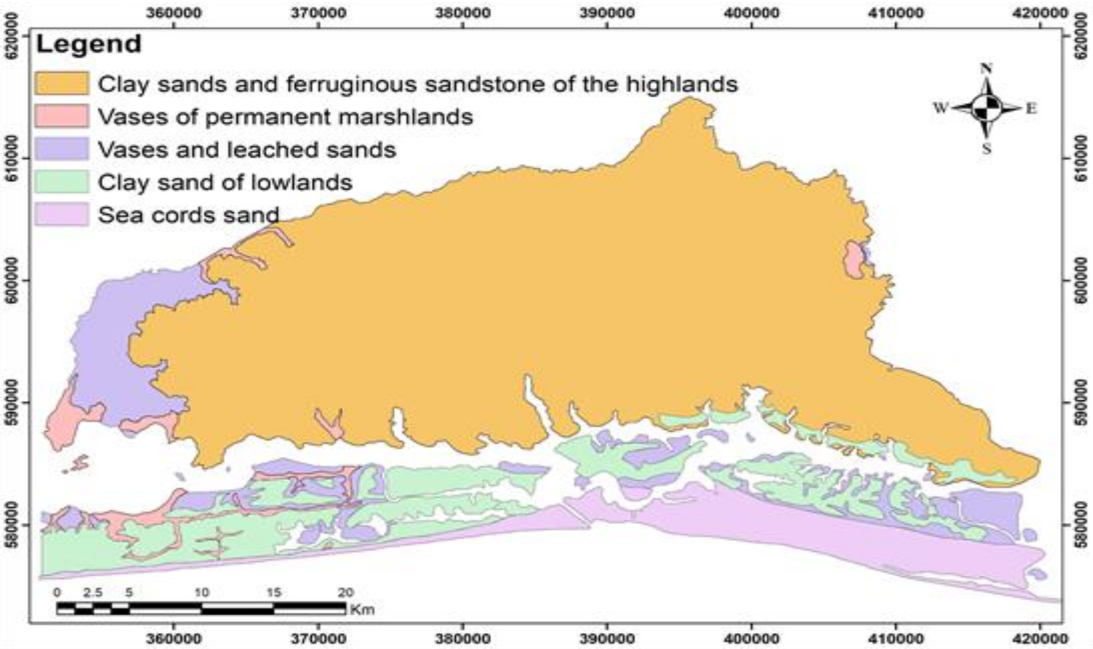

Figure 18 Geological map of Côte d'Ivoire (West Africa)

3.6 Pedology

The soils of the Abidjan region are ferralitic, hydromorphic, and recent. The ferralitic soils found on the low and high plateaus have a structure in which the alteration of minerals is complete. The establishment of this soil texture comes from the process of feralization, which developed under the influence of paleoclimatic factors and very old types of vegetation. The abundance of rain and the high temperatures lead to the constitution of a staggered profile with:

- A first horizon that is not very thick, low in humus, but high in organic matter;
- A second horizon, very thick, with a predominance of red or brown hue and an abundance of iron and alumina;
- A third clay horizon, compact and somewhat permeable;

A basic horizon is very thick and of variable hue related to the nature of the source rock. Hydromorphic soils are the second important soil element in the Abidjan sector. This hydromorphic was caused by a soil evolution dominated by an excess of water. Recent and very little evolved soils, although spatially smaller than the other two, have developed in the coastal sector, presenting rather coarse facies where sandy elements dominate, which is called coastal dunes.

3.7 Hydrography

The region is crossed by many rivers of varying directions: - the Agnéby and the Me, which delimit the area, are generally north-south. These are the largest rivers in the region; - the Banco, the Gbangbo, and the Anguédédou are small rivers in a North-South direction; - the Djibi and the Bété, which flow into the Aghien lagoon, are in a North-West/South-East direction. The coastline is interspersed by a lagoon system (Ebrié lagoon) parallel to the Atlantic Ocean. Therefore, all these rivers and lagoons drain into the Abidjan aquifer. Runoff coefficients vary by stream, they are relatively low for the rivers Me and Agnéby; this is related to low slopes and canopy density. These coefficients are high for other rivers because of the deforestation that affects these areas.

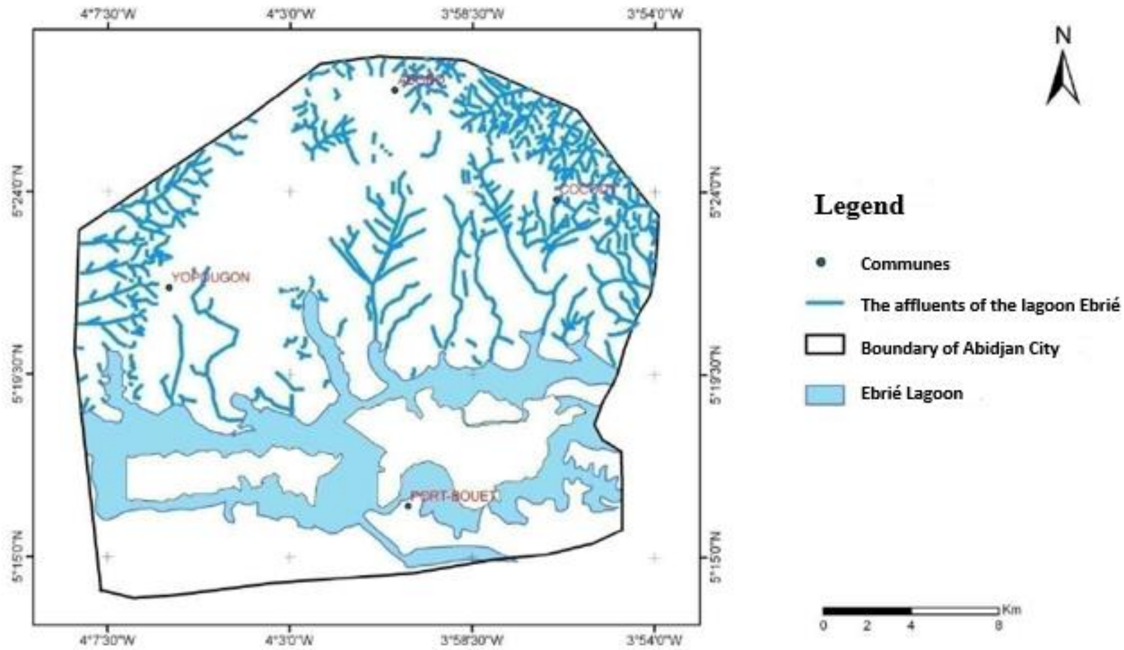

Figure 19 Representation of the Ebrie lagoon and the various rivers present in Abidjan and the entire coastline of Côte d'Ivoire from Avy Stéphane Koffi et al. (2017)

3.8 Hydrogeology

The aquifers of the coastal sedimentary basin are fairly homogeneous and highly permeable aquifers and are composed of three aquifers: The Quaternary aquifer, the Continental Terminal aquifer, and the Maastrichtian aquifer. The Continental Terminal aquifer covers the entire surface of the coastal sedimentary basin in the form of high plateaus, with the exception of the Quaternary littoral area. This aquifer is unconfined and includes four levels from top to bottom. The formations encountered are discontinuous lateritic cuirass and locally sandy clays or clayey sands, coarse fluvial sands, mixed clayey sands and black clay, and gravelly sands. However, most formations are clayey sands interspersed with variegated clay.

3.9 Flooding event

A number of things happen once a rainfall event starts. This section describes the processes and the sequence of events that occur. An illustration of the whole process and the failure mechanisms can be seen in Section II. Depending on where the precipitation lands, different events start, some of which are interconnected. Part of the precipitation will be intercepted by shrubs, grass, and greenery in general. This water will leave the urban flood event by evapotranspiration.

The rest of the precipitation will fall to the surface, where in this particular case it will not infiltrate due to an impermeable surface. The water will immediately run off and become overland flow. Overland flow can interact with the environment in a number of ways. For one, it can become a depression storage area. In certain locations, water can get stuck and stay there until it evaporates (including buildings it enters). Precipitation that falls into depression storage will stay there as well. The capacity of the depression storage can be exceeded, in which case the storage will overflow. Overland flow can also erode the soil, as is the case in certain locations in Abidjan.

Eventually, the overland flow will flow into drainage channels or the main channel around the circumference of the Riviera Palmaraie. At the beginning of an extreme rainfall event, the drainage channels are able to cope with the flow and guide it through the channel and culverts under roads to the main channel. Local inundations will occur when the channel flow becomes large enough to either exceed the capacity of the channel or the capacity of the culverts. When the main channel overflows, the drainage channels will overflow as well, and inundation will occur not only next to the main channel, but also around the drainage channels. Both the drainage channels and the main channel also receive water from precipitation. During the course of the rainfall event, the discharge in the channel increases and the water level rises rapidly, according to locals (van Overeem & Steenbergen, 2015).

3.10 Data collection for hydraulic modelling

Hydraulic data has often been collected for a long time (decades or centuries) in developed countries. However, in developing countries such as Cote d’Ivoire, data has not been collected and archived well. In fact, recorded data is frequently saved in various computational formats, and some of them are still only available as paper chart records or tabulated data. Furthermore, only the main navigation channels within the Riviera Palmaraie district are frequently surveyed and gauged, and not all gauging stations are used to record both stage and discharge. Such issues in collecting and storing relevant data may lead to insufficient input data for building and calibrating hydraulic models. The data used in this study, on which we were based to carry out the hydrodynamic modeling of the district, is as follows:

- Rainfall data were collected in order to test the model's sensitivity to this input variable under the hypothesis of rainfall uniformity over Abidjan's Riviera Palmeraie district. To evaluate the model, two real-life cases of rain events on June 18 and 25, 2020 The rainfall and flow data used in this study were collected in the first analysis data from the pluviograph network of the EVIDENCE project. They extend over the entire month of June 2020. This period covers the two events. We were based on measures carried out at "Notre Dame Paix" and "Cité Soeur", assuming that the rain is uniform over the whole area, otherwise at the channel level, we note contrary behavior.

- water level and maximum flow rate of the event of June 25, 2020 at the stage of the Ministry drain.

- Satellite image (excluding flooding) and OpenStreetMap map.

- The delimitation of the Riviera Palmeraie watershed and Minister Street is formed from the lines of ridges or watershed lines.

- Files of hydrometric stations, only one of which is located in the Rue Minister study area, but which was established following the deadly flood and landslide events of 2008.

- A Lidar Digital Terrain Model (DTM) from the Shuttle Radar Topography Mission (SRTM) database with 30-meter spatial resolution

3.10.1 Modeling approach

Different methodologies have been applied in this study in order to achieve the goals of this research. The methodology comprises a few phases, as known:

− Terrain preprocessing using the Digital Elevation Model (DEM), SW2D, and SMS for the preparation of input data models, running the simulation, and then getting the results of the simulation. The hydraulic modeling started by:

− SW2D model development;

− SMS mesh generator

The following chart, Figure 20 illustrates the overall methodology used in this study.

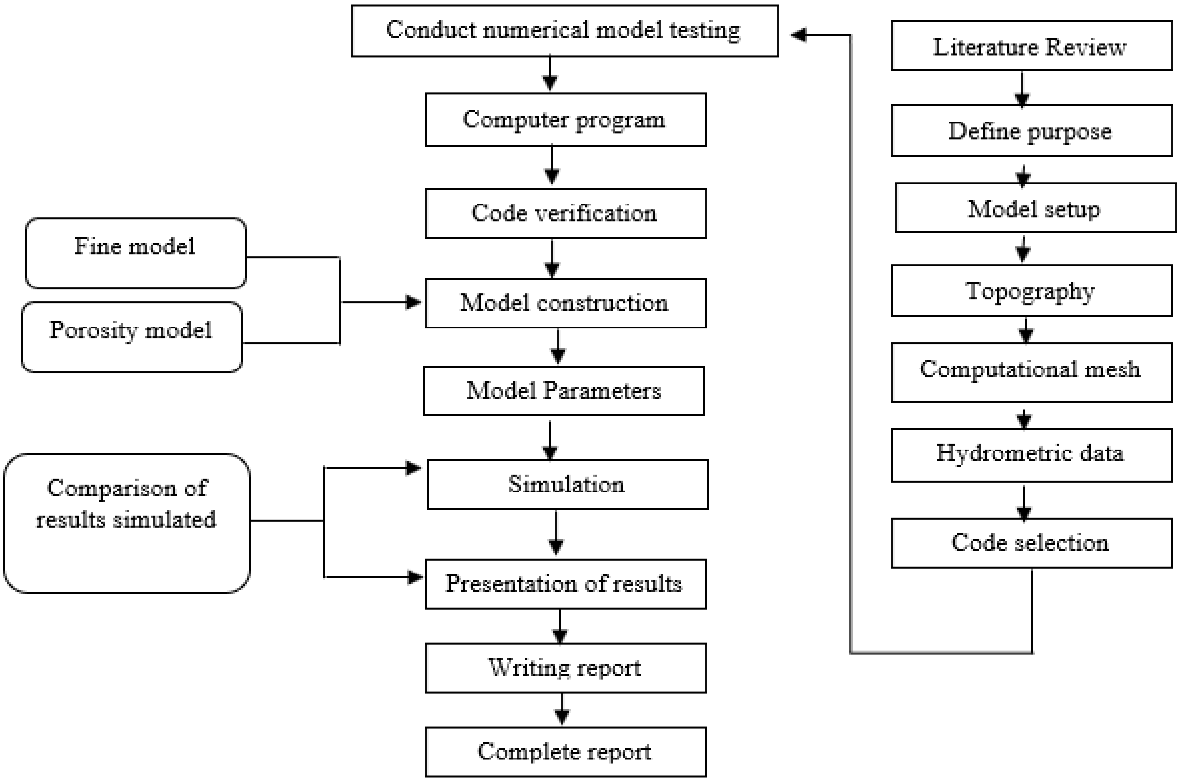

Figure 20 Methodology Flow Chart

3.11 Data pre-processing

Preprocessing brings together all the processes of creating the digital model of the terrain and its derivatives. The 2D models were created using a DEM, incorporating channel bathymetry, buildings, and surface topography. Channel geometry for the 2D cross-sections was extracted from the model DEM. The model DEM was also used as the computational mesh in the 2D simulation after re-sampling at lower resolution.

3.11.1 Digital Terrain Model and mesh Generation

3.11.1.1 Digital Terrain Model

The quality of topographic data is certainly the most essential data for numerical modeling. They allow one to obtain an accurate representation of the surface and elevation of the terrain in order to depict the aspects of the hydraulic course in the region. Thus, DTM (Digital Terrain Model) databases georeferenced points according to a specific projection system in order to model by software 3D topographic maps of the study area, on the basis of which calculations of velocity, water height, and flood area are performed. They are thus required for any 2D modeling: in preprocessing for mesh creation, processing for hydraulic calculations, and post-processing for visualization of the results. It is the visualization and processing of these results that then allows risk and impact assessment (Seyoum, 2013). The accuracy of the results is very sensitive to the resolution of the field data (Néelz & Pender, 2009). One of the major advances in hydraulic modeling is the democratization of DTMs obtained by laser remote sensing, or LiDAR (Light Detection and Ranging). This technology allows the measurement of distance by analyzing the reflection of a laser on a surface. By combining it with a global georeferencing system and an inertial measurement unit, all installed in an airplane, this system can collect accurate and dense topographic data over a large area more quickly and more economically than the contour method (Seyoum, 2013).

3.11.1.2 Mesh generation

For high densities of DTMs, running the hydraulic model over this domain would result in unrealistic computation times, as the Saint-Venant equations apply to each vertex. Thus, the distinct positions where the variables are to be computed and defined on a digital mesh, a spatial discretization of the continuous domain on which the modeling equations are solved (Mavriplis, 1996). The mesh of the predefined study area is realized with the SMS Aquaveo software. The force lines were drawn around the streets using a satellite image of the study area. Assuming that the building constitutes an impermeable boundary, it is not physically taken into account but only in the context of the variation of the porosity during the study of the porosity model treated thereafter. During the realization of the lines of force, it is essential to ensure the verticality, the perpendicularity of the lines, and the equality of the number of nodes on both sides of the streets in order to have the largest possible number of rectangular meshes. Indeed, defining quadrangular meshes, oriented in the direction of the flow, avoids problems of numerical diffusion and saves computing time compared to triangular meshes. The SMS software allows local refinements of the mesh. This one take place in all the intersections given their important role in the distribution of the flows within the urban environment while keeping a constant and looser distance between the nodes of the other streets. It is also necessary to ensure that we have several meshes per street. The modeled 2D areas are represented by rectangular meshes in general and some triangular meshes. The total number of meshes is about 174922, with an average area of 5 m2. The model relies on the 2dm file is created by the SMS software to obtain the geometry and information about the nodes and meshes.

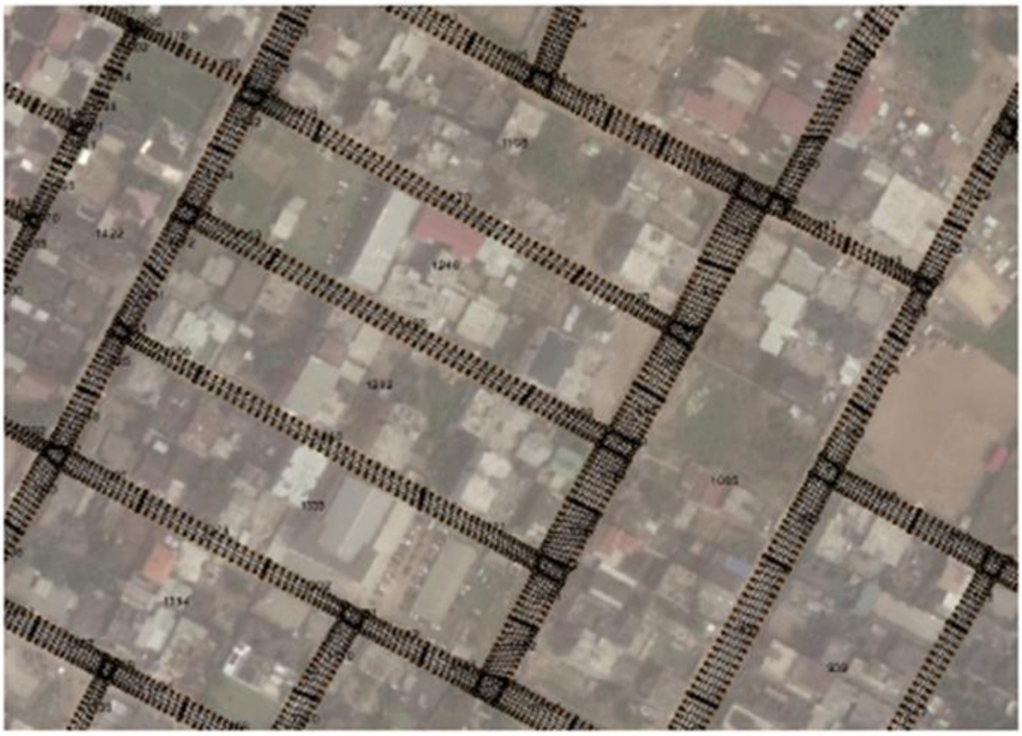

Figure 21 Extract of the study area mesh

3.12 Hydrodynamic modeling of urban floods in the study area

3.12.1 Hydraulic modeling

The purpose of hydraulic modeling is to characterize the physical parameters that describe the flow. It consists, through an adapted computer code, of the numerical resolution of the free surface flow equations (the Barré de Saint-Venant equations), which are based on the conservation of mass and energy.

One-dimensional (1D) modeling is most often used because it is based on the assumption of an axial flow. The flow is assumed to be rectilinear so that all the sections are perpendicular to the axis of the flow. This assumption simplifies the solved equations and subsequently reduces the computation time. This type of modeling is suitable for watercourses with a privileged direction of flow with little overflow.

Two-dimensional (2D) modeling, freed from the axial flow hypothesis, allows a finer and more precise characterization of the flow by taking into account the multidirectional flows and the obstacles present. Consequently, this type of modeling requires more data and a longer computation time.

There are also other calculation codes which couple between modeling (1D) and modeling (2D), such as the shallow water 1D and 2D codes developed at the Hydro Sciences Montpellier laboratory.

⇒ In an urban environment, it is therefore necessary to use two-dimensional modeling (2D) because of the strong direction changes at street crossings.

3.13 Model description

The complex interactions between the main channel and the floodplains during floods are important flow features and may not be neglected (McMillan and Brasington 2008). Even excessively simplified 1D flow models or excessively simplified 2D models are unable to reproduce satisfactorily the mass and momentum exchanges between these two flow areas, especially when densely urbanized floodplains are concerned. Therefore, simulations of floodplain inundation flows are conducted here with the two-dimensional numerical model SW2D, developed at the Hydro Sciences Montpellier laboratory.

3.13.1 Modeling equations

The extent of the dangers associated with city flooding in the future requires an enhancement of modeling systems. Innovation in this area is immediately linked to the improvement of lookup on these points: the traits of flows in cities, the system of equations describing the bodily phenomenon, the improvement and numerical calibration of these equations, and eventually the validation of the models by means of real statistics from previous and documented activities (Alcrudo, 2004).

To model the movement of a Newtonian fluid and the drag forces that keep it back, researchers Henri Navier and George G. Stokes independently installed the integral equations of fluid mechanics. These, oftentimes referred to as the Navier-Stokes equation, are nonlinear partial differential equations in the non-stop media approximation.

3.13.2 Governing equations

The governing equations for fluid flow are developed using continuity and the equations of motion. The resulting relationships, known as the Navier-Stokes equations, can be applied in three dimensions to solve complex fluid flows. Simplified one-dimensional and two-dimensional relationships, known as the St. Venant equations, are applied where a more complex description of flow is not necessary. Due to computational limitations, hydraulic models have typically solved the 1D St. Venant equations, which are computationally efficient but cannot accurately model complex topography. Recent advances in computational capacity have made 2D solvers more feasible. A 2D model can accurately model complex topography but is not as computationally efficient as a 1D model and has difficulty modeling in-channel structures. The advantages of both types of models can be combined by coupling 1D and 2D models.

When developing a hydraulic model, uncertainty must be accounted for. Uncertainty in a hydraulic model can come from a number of sources. Data collection errors can come from instrument error, resolution of collected data, and collection methods. Further uncertainty in simulation results can arise from assumptions made during model development, such as the choice of mesh resolution, methods of modeling structures, and methods of calibration.

3.13.3 Mathematical Model

The method advocates using a finite volume scheme to solve two-dimensional shallow water equations in the conservative form on an unstructured mesh composed of quadrilaterals and triangle cells that are constrained by building walls. With the idea of porosity in mind, the shallow water equations are written in a conservative form with the concept of porosity by [Soares-Frazão] [3] as follows:

$$\frac{\partial w}{\partial t} + \frac{\partial f_1}{\partial x} + \frac{\partial f_2}{\partial y} = S \qquad (1)$$

With

$$w = \begin{bmatrix} \emptyset h \\ \emptyset hu \\ \emptyset hv \end{bmatrix} \; f_1 = \begin{bmatrix} \emptyset hu \\ \emptyset hu^2 + \emptyset \frac{gh^2}{2} \\ \emptyset huv \end{bmatrix} \; f_2 = \begin{bmatrix} \emptyset hv \\ \emptyset huv \\ \emptyset hv^2 + \emptyset \frac{gh^2}{2} \end{bmatrix} = \begin{bmatrix} 0 \\ S_{P,x} \\ S_{P,y} \end{bmatrix} \qquad (2)$$

where ϕ is the porosity, g is the gravitational acceleration, u and v are the velocities in the x and y directions, h is the water depth, Sp, x and Sp, y are the source terms resulting from the variations in the bottom slope and variations of porosity in the directions x and y.

The source terms are given by:

$$S_{P,x} = \emptyset\, gh\, S_{0,x} + g\frac{h^2}{2}\frac{\partial \emptyset}{\partial x} = -\emptyset gh\frac{\partial z}{\partial x} + g\frac{h^2}{2}\frac{\partial \emptyset}{\partial x} \qquad (3)$$

$$S_{P,y} = \emptyset\, gh\, S_{0,y} + g\frac{h^2}{2}\frac{\partial \emptyset}{\partial y} = -\emptyset gh\frac{\partial z}{\partial y} + g\frac{h^2}{2}\frac{\partial \emptyset}{\partial y} \qquad (4)$$

z is the dimension of the bottom, and S_0, x, S_0, y are the source terms of the bottom slope in the x and y directions.

3.14 Software and calculation code used

3.14.1 SMS Software

The tool used to perform this simulation is the software Surface-water Modeling Software (SMS), which is developed by Aquaveo, a group of engineers that have joined together their experiences to build a surface-water modeling solution. SMS has been used, such as:

- ✓ A model-independent GIS for numerical modeling
- ✓ It uses a conceptual approach
- ✓ Multiple 2D/3D model user interface
- ✓ uses the model setup, which is for mesh generation and refinement, interpolation of elevations, assigning boundary conditions, defining spatially variable roughness, assigning components and visualizing model results.
- ✓ It uses the Generic Mesh Modul, which is used to create, edit, and visualize mesh data, also referred to as unstructured or flexible meshes, meshes defined by nodes and elements/cells, and add boundary conditions.

SMS allows users to choose between a structured and unstructured mesh, but also change the mesh sizes. A tool for testing the mesh's quality is also included in the software. SMS provides 1D and 2D modeling, as well as a unique conceptual model approach, and it allows for the representation of results in a variety of formats (vectors, level curves, etc.) and includes an animation module.

In this study, we applied the mesh design tool, which was read by the SW2D hydraulic modeling code.

3.14.2 Calculation Code used

The SW2D calculations code is a software chain developed by the Montpellier HydroSciences Laboratory (UMR) of the CNRS, the IRD and the universities (Montpellier 1 and Montpellier 2). This code, developed for research purposes on numerical methods, has nevertheless been used to date by two engineering firms (including Ginger Environment & Infrastructures) for a total of about 20 studies since the beginning of 2005. The classical two-dimensional Saint-Venant equations have been modified to be able to deal with a macroscopic approach by porosity [3]. The conservation of mass and momentum equations in each of the flow.

The code used is SW2D, which is a two-dimensional computing code for free surface flow simulations developed at the Hydro Sciences Montpellier laboratory since 2002. It solves several variants of the shallow water equations on unstructured grids using finite volume techniques. The code is made up of numerous executables that must be run in order. There are two elements to each executable name. The application's name comes first, followed by the version number. For this study, ex_IP_11d.exe is the 11d version of the executable "ex," which is the application that extracts the results from the result files. The modelling sequence is explained by three steps below:

— Step One: The Geometry Process:

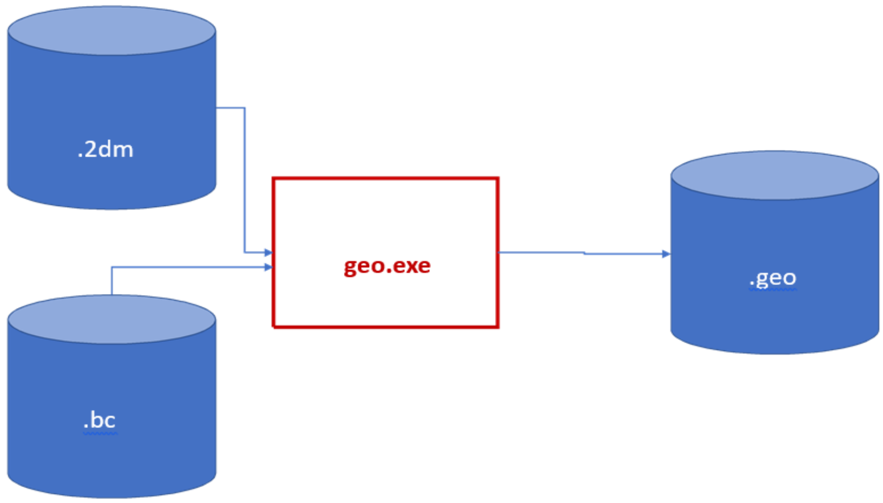

Figure 22 geometry process

— Step two: run simulation.

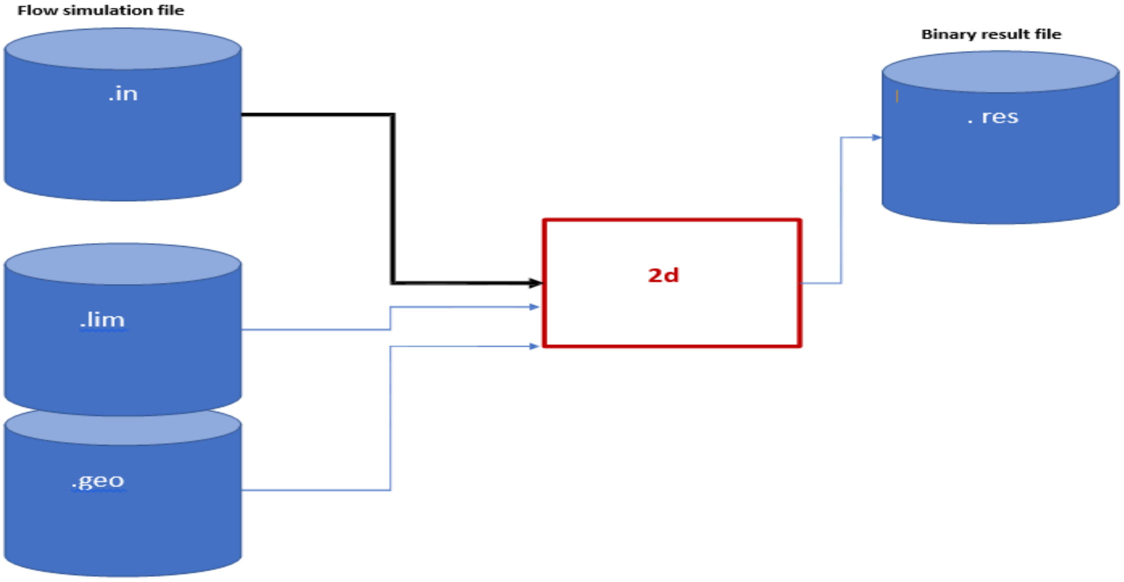

Figure 23 run simulation

— Step tree: maps extraction process

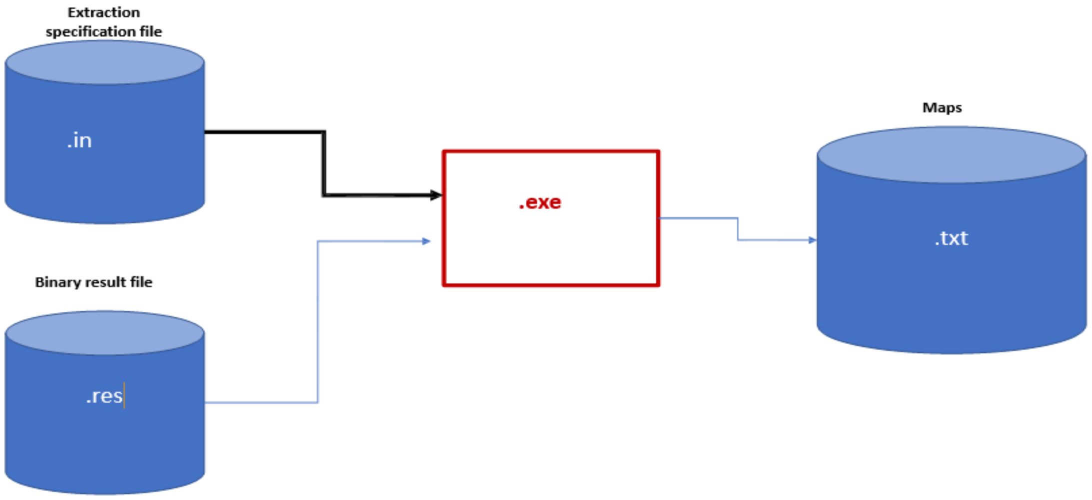

Figure 24 maps extraction process

This code includes tree main elements as follows:

- Geo, a mesh and geometry compiler, to translate data from commercial SMS packages into a binary file with all the geometric information and connectivity tables.
- Sw2d, the simulation engine, runs the simulations using the binary file created by geo (along with extra parameter files).
- ex, the extraction utility for extracting maps from binary result files.
- The results are composed of two types: maps, which are saved in a binary file (.res) at regular intervals, and time series, which are saved at random intervals and stored in the text files.

3.15 Model application

In the subject of water management, numerical modeling is nowadays widely used in fluid mechanics, particularly hydrodynamic modeling, and can be used to better understand and anticipate flood flow in urban areas, ensuring the safety of property and people. Hydrodynamic models are mathematical models that solve the continuity and momentum equations to simulate fluid motion. Depending on their modeling paradigm and specifically on their specific representation of the flooding domain, models can be classified into one of three dimensions: 1D, 2D, or 3D models:

1D shallow water models (SW) are very efficient in terms of computation, but their hypotheses do not allow them to simulate complex flow features (2D, or even 3D).

2D shallow water models (SW), widely used in urban flood modeling, are a good compromise between 1D and 3D (relatively limited computational resources but correct flow simulation accuracy) as discussed in the present work.

3D simulations, which are often based on Reynolds averaged Navier-Stokes equations with a turbulent closure, are typically used at the local scale, such as the crossroad scale (Bradbrook et al. (1998); Neary et al. (1999); Huang et al. (2002; Ramamurthy et al. (20071; Li and Zeng (2009, 2010)). The 3D models are too costly for systematic simulations at the district/city scale and are difficult to calibrate (wall function and turbulence model parameters). In this thesis, 3D models are not used.

Numerical model is a common method for the numerical resolution of fluid flow equations. In this section, we are going to explains the basic steps to conduct a hydraulic problem in the numerical model. The pre-and post-processing stages are crucial. The finite element meshes, or cross-section entities, must be generated and saved to model-specific files, along with the related boundary conditions needed for analysis. Post-processing is needed in order to obtain solution data like flow velocity and steady water depth etc. The procedures can usually be broken down into a few stages, as shown below:

1. Data collection for model input parameters;
2. Draw the geometry of model;
3. Grid generation and mesh editing;
4. Apply boundary conditions and initial condition;
5. Adjust the model control such as the time step size;
6. Open a command prompt and enter the simulation engine’s name (2d2.8b);
7. Enter requested input file name Fmesh.in for fine model and Pmesh.in for the porosity;
8. The simulation has begun. The simulated time is shown regular intervals and control the simulation progress. After that the simulation took 48 hours for fine model and few minutes for porosity model to gets results. The time of simulation depends of the computer performance;
9. Examination of the right solution.

3.16 Data Collection for Model Input Parameters

Data such as rainfall, water level and maximum flow rate, Satellite image, Delimitation of the Riviera Palmeraie watershed, hydrometric station files and Digital Terrain Model (DTM), flow conditions at boundaries; discharge rate, water depth(h) and free surface elevation (z) are required as input parameters. Those data obtained either through simulation and experiments results.

3.16.1 Model Geometry

The geometry was input into model as point coordinate in function of x and y, which are referred to longitudinal and lateral direction respectively. Meanwhile coordinate z represents the bed level from datum for each point. The value of z was created by using interpolation method. Note that for experiment a test cases, the coordinate z was interpolated by using data from slope checking. Other critical elements such as points on weir, contraction and bridge pier should be inputted into the model. Figure 3.26 shows an example of contraction geometry in a numerical model.

3.16.2 Grid generation

In the practical application of 2D models, the grid generation is a decisive step. Often it decides upon success or failure of a model, both with respect to the quality of the results as well as the time consumption for the user.

Application of the Finite-Volume-Method (FVM) requires “smooth” grids. That means neighboring cells should have similar dimensions. When using triangles, the appearance of acute-angled triangles (i.e. triangles with one angle larger 90°) should be avoided. Digital terrain models on the basis of TINs (Triangulated Irregular Networks), which are the basis for the spatial discretization in 2D, often contain such triangles.

That means the triangulated DTM is usually not directly utilizable as discretization grid.

3.17 Initial Condition

Initial condition is always required in hyperbolic shallow water equation. Since the interest is in steady-state results only, the first-order backward difference in temporal derivative was chosen. Therefore, initial condition for one-time step of old data (t= -1) was created in an initial file called hot start file.

The hot start file contains data such as flow rate, velocity and initial depth for each mesh node when time = -1. This file will be over written by the model and replaced with latest result data.

For this reason, a copy of hot start file was always made.

For the starting time of the simulation at any computational node the values of the 3 variables (h, q, r) must be given. If no suitable information is available, one of the following options is often chosen in practice:

(1) Assumption of fluid at rest, constant hydraulic head z = zb +h = const, q = r = 0.

(2) Assumption of a dry channel („dry start "): h = q = r = 0.

(3) Using results from an earlier simulation as initial conditions („hot start ")

3.18 Flow regime

The "classical" SW2D calculation code applied in this study treats only the transient regime although it is able to represent any stationary phenomenon by keeping the same conditions during a very long time. The transient regime integrates the time factor and thus allows to work on the reality of a flood event through the consideration of a hydrograph. The duration of the simulated rainfall is 4 hours, so we are well within the framework of the transient regime.

3.19 Boundary Conditions

Model equations constitute a hyperbolic initial boundary value problem. The required boundary conditions are determined using characteristic method and assigned by selecting a specific node or node string.

The number of boundary conditions is equal to the number of characteristic half-planes that originate exterior to the control and enter it. For example, if the inflow is supercritical, then all information from outside the control is carried through this boundary; if inflow is subcritical, downstream control effect will provide the depth. Thus, depth is not needed in this inflow boundary.

In the same manner, if outflow boundary is supercritical, no boundary condition is specified because all information can be determined within the control domain. If outflow is subcritical, then the depth should be provided as tailwater.

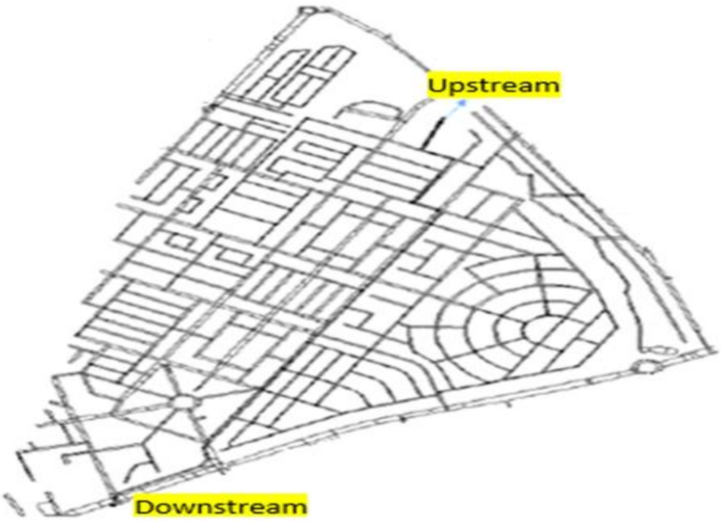

Figure 25 shows the Number of required boundaries for the 2D-Shallow water equations

Depending on the flow regime the variables must also be given at the model boundaries. The type of variables depends on the flow regime and is determined by the number of characteristics which arrive at the boundary from outside:

Table 3 Number of required boundary conditions for the 2D-Shallow water equations

Flow regime	Inflow bound	Outflow bound
Subcritical	2	1
Supercritical	3	0

Setting meaningful boundary conditions is done in analogy to the 2D case. At an inflow boundary the flow rate Q is given as inflow hydrograph together with the direction of the inflow. For an outflow boundary the following quantities are used:

(1) free surface elevation (z) (hydrograph)

(2) water depth(h) relationship

(3) Slope of water surface or energy slope

Suggestion: A comparison with a physical model can simplify the choice of boundary conditions.

Boundaries which can be realized in a physical model will as a rule also lead to reasonable results in a numerical model.

3.20 Model Run

During this process, only variables were stored during the simulation can be extracted from the result file for display purposes. It is recalled that the codes of the variables to be stored during a given simulation can be found at the bottom of the simulation input file for the 2d executable. After simulated the variable has been stored in a specific variable code in the result file given in the table below.

Table 4 Variable codes

Code	Variable	Symbol
1	Water depth	h
2	Free surface elevation	z
3	Unit discharge	q_x , q_y, $\|\mathbf{q}\|$
6	Flow velocity	V_x , V_y, $\|\mathbf{V}\|$
9	Froude number	Fr
10	CFL number	Cr
11	Water depth under the ground surface	η
12	Specific head $(h + V^2)/(2g)$	H_s
13	Hydraulic head $(z + V^2)/(2g)$	H ou H_t

3.21 Results Examination

Results from model were examined for reasonableness. To do this, a postprocessing step was needed to open results in graphic or table mode. For this reason, a software named Surface Water Modelling System 13 (SMS) was used. Results are presented in contour or vector mode for viewing.

4 RESULTS AND DISCUSSION

4.1 Introduction

This study involves numerical model simulation and data measured. The implementation of numerical simulations is based on SW2D code developed at the HydroSciences Montpellier laboratory which we proposed of 2D models (fine-porosity). For every test case, results from both sources are presented together for comparison purpose. Input parameters for each simulation are provided and results from both sources were analyzed.

The various simulations carried out on the Riviera Palmaraie district of Abidjan firstly allow to highlight the importance of the interactions of 2D models (fine-porosity) within the framework of the modelling of extreme events. Secondly, the comparison of water levels (z) graphs and water depth maps will be made.

A third section will focus on the comparison between the difference between fine and porosity models, showing the visualization of spatial maps.

In addition, Flood inundation map was developed based on water height and velocity simulated in hydraulic modeling. The results were directly visualized in GIS.

We have chosen to simulate the rainy event that took place on 06/25/2020 with 4 hours of rainfall. In fact, the only reason why we are interested in this event is that the duration observed allows us

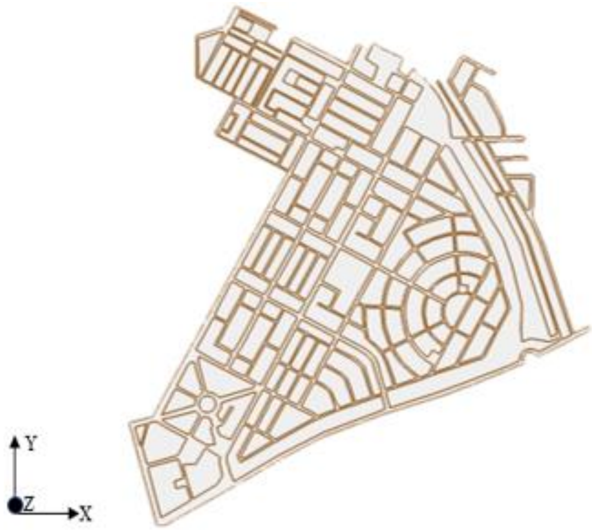

Figure 26 Simulation domain

to perform some simulations with the sequential version of our code. Rainfall occurred first to the upstream of the city and then the storm centre moved to the downstream of the city. It persisted over the city centre and deposited a large amount of rainfall in the inner city of district.

The rain intensity fluctuates strongly around 124mm/h (see Figure 27).

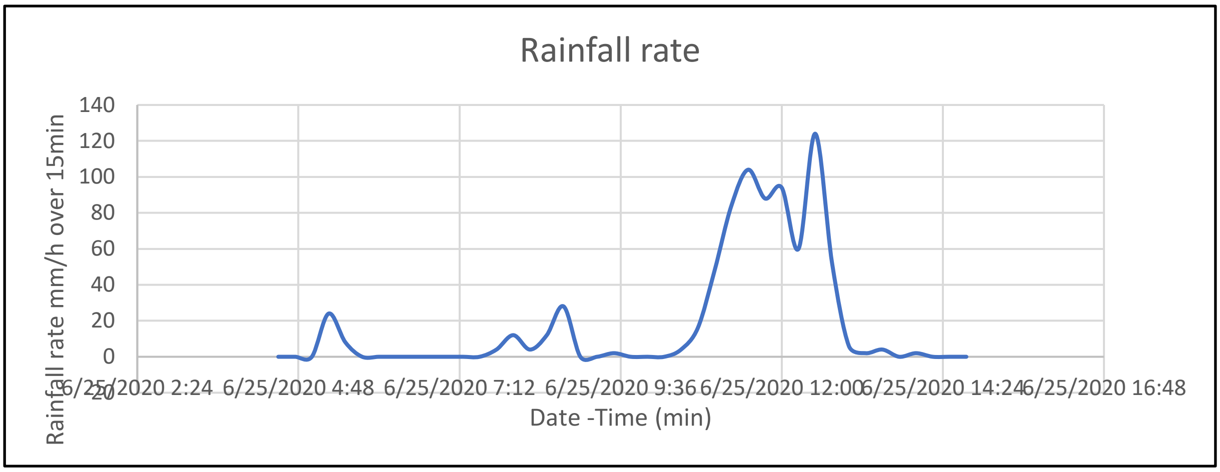

Figure 27 Rainfall intensity measured at the Centre F12 station during the 25th June 2020 flood event occurred in Riviera palmaraie; rainfall time series with the highest rainfall amount.

4.2 Results and Discussion

In this section, the simulations result of models are compares next, we discuss the results of the hydraulic simulations. In order to proceed to the analysis of the results applied on the different models, and thus to be able to compare them, the graphs as well as the visualization results.

Figure 28 show the difference linear variation of water elevations at probe point z1. In each graph of results obtained over the simulated events of 4 hours rainy and the results obtained by simulation of the 2D fine and 2D porosity models are compared. For the graph shown, for both simulated model, the water level propagation speed from the porosity model is in the order of a few centimeters, which is fairly limited considering that the water levels are a few centimeters at that point. One possible reason must be caused by the differences of the conveyance porosity thus appears to be insufficient to represent urban area influence and should be associated with a flow direction.

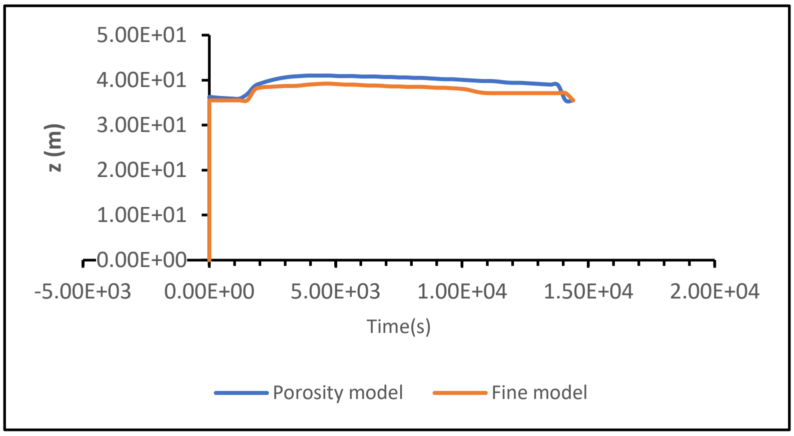

Figure 28 Comparison of 2D fine and 2D porosity models showing water levels (z) as a function of time at probe 1 in the models

The water level in the graph show little to no convergence since 2D fine model is only a few centimeters lower than 2D porosity model. It is not clear what causes this non-convergence, but it is clear that it is difficult based on the results of porosity model. This must be caused by the differences in outflow from the urban area. However, these differences are not very large but it was to be result expected since it is exceeding the fine model. Figure 29 : show the variations of the water levels at probe 2. The graphs result obtained gives the comparison of the 2D models. At the beginning two models are follow the same line and at time T= 504 s after there is a divergence between lines. The water level line rises too quickly in the fine model with time evolution compared to the porosity model which line start increasing in cascade at time T= 506 s with time evolution. Indeed, the water level of both fine and porosity models at probe z2 drops at the same point then obviously a few times later, lines crossed at the starting point. As we can see, the effect of the water level of fine model at that probe confluence is significant very important for floods occurring. Fine model is considered as the reference simulation in this work then the results obtained is sounds reasonable.

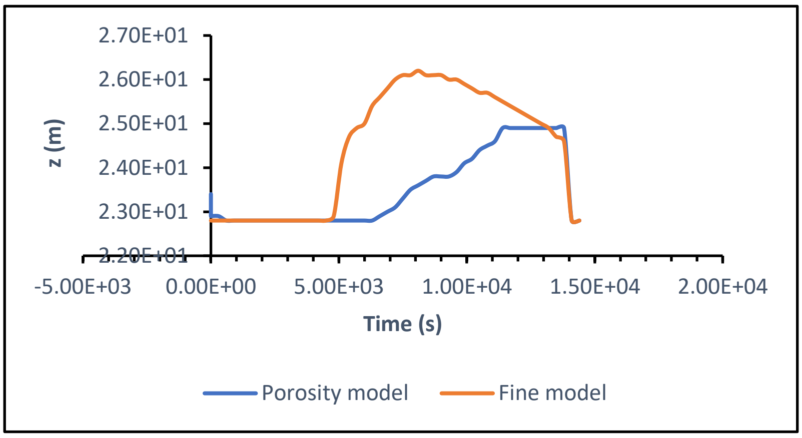

Figure 29 Comparison of 2D fine and 2D porosity models showing water levels (z) as a function of time at probe 2 in the models

However, the porosity model that have been used is to ensures a considerable gain in calculation time and especially in mesh design and does not pose any constraint for scale of the whole agglomeration. Moreover, we observe a systematic shift between the fine and porosity model's lines for the lowest water level happens from the porosity model. This shift can be explained by the undulations of water flow. Figure 30 shows the results of water levels at probe z3 simulated results using fine model presented as reference model in this work.

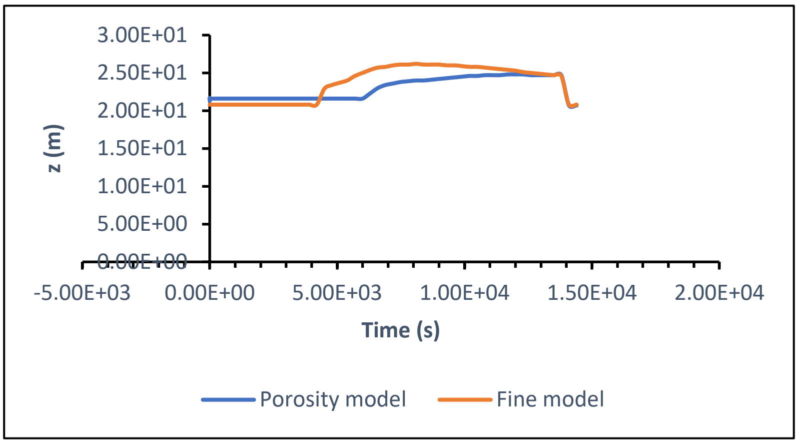

Figure 30 Comparison of 2D fine and 2D porosity models showing water levels (z) as a function of time at probe 3 in the models

Compared to the porosity model, we can see in the graph a significant improvement. More specifically, the line is much better approximated (compare Figure 28). This, however, is achieved at the expense of overestimated water level of fine model at the upper line at the probe and strongly underestimated from the porosity model which line is below. We noted general observation is that all the fine model of water level computed by fine model remains significantly stronger in the city than that computed by porosity model.

The Figure 28, Figure 30 shows the comparison between fine 2D water levels and porosity model values at different probe over the time periods. The proposed model shows very good agreement with the measured water surface at probe, from which it can be concluded that the proposed model shows a desirable accuracy and is able to predict the water surface profile of a rapidly varying flow affected by depth evolution. However, Figure 29 show a large shift in the middle between two models, this graph testifies to the variability between modeling methods, the results being very disparate. On the other hand, the curves of the model time steps both offer a progressive increase before displaying divergence between models, although the general shape of the water level variations remains the same at the beginning and end of the event. The strength of this test case is that it offers actual observed data on the maximum water level that the flooding caused. The simulations are computationally stable in all cases. The variations noted in the water level are associated with surface flow runoff and often in synchronization with the intensity of rainfall.

4.2.1 Visualization of results

Visualization of results is an indispensable part of modeling. However, many models neglect this aspect and leave the user with the difficult task of finding a way to effectively present the results obtained by the model. It seemed therefore, during the development of two-dimensional models, to provide a set of procedures allowing to draw basic figures for the main outputs. Moreover, with the realization of scenarios, it is very pleasant to have ready-made routines allowing to draw figures with always the same layout and this without having to repeat each time of the code.

4.2.1.1 The maps

The surface module produces a number of spatialized results. This is notably the case for water levels, water depth, free surface elevations and rainfall amounts in the watershed. In the context of calculating flood scenarios that surrounds the development of two-dimensional models, it is obviously the surface water level maps that have attracted attention.

The information is presented in the form of a raster stored in a text file with, as for all rasters used as input to the model, a value per pixel. Whether using a GIS such as MapInfo or QGIS, or a mathematical tool such as SMS, the visualization of this type of results is easily implemented through various algorithms implemented in the software. The problem with these procedures is that they allow for a nice visualization, but they tend to average the values between them to smooth out the features of the figure. However, it may be preferable to set up a visualization of the values as they are given by the model. In this work, some of the figures were plotted with SMS software (e.g., in Figure 31, Figure 32).

Since the surface model provides a map by time step, it is possible to follow the evolution of the selected information during the modeled event.

Figure 31 (a-e) show the spatially varied results obtained for the water depth by the two-dimensional model of fine and porosity at different times t =1 hour; 2 hours; 3 hours and 4 hours. The water depths at different models are reasonably well predicted, and, as expected, there are not much differences between two models in terms rainfall time series observed during simulations. The differences are observed at the end of the constant rainfall time T= 4 hours, the maximum difference value is 0.7 m and minimum value is about the 0.1 m. Water depths in the receiving water body were very high and were affecting the water levels in the urban area. Indeed, the water depth above still water level. This leads to a balance between the flux gradient and source terms in a Godunov solver, and permits application of wetting and drying

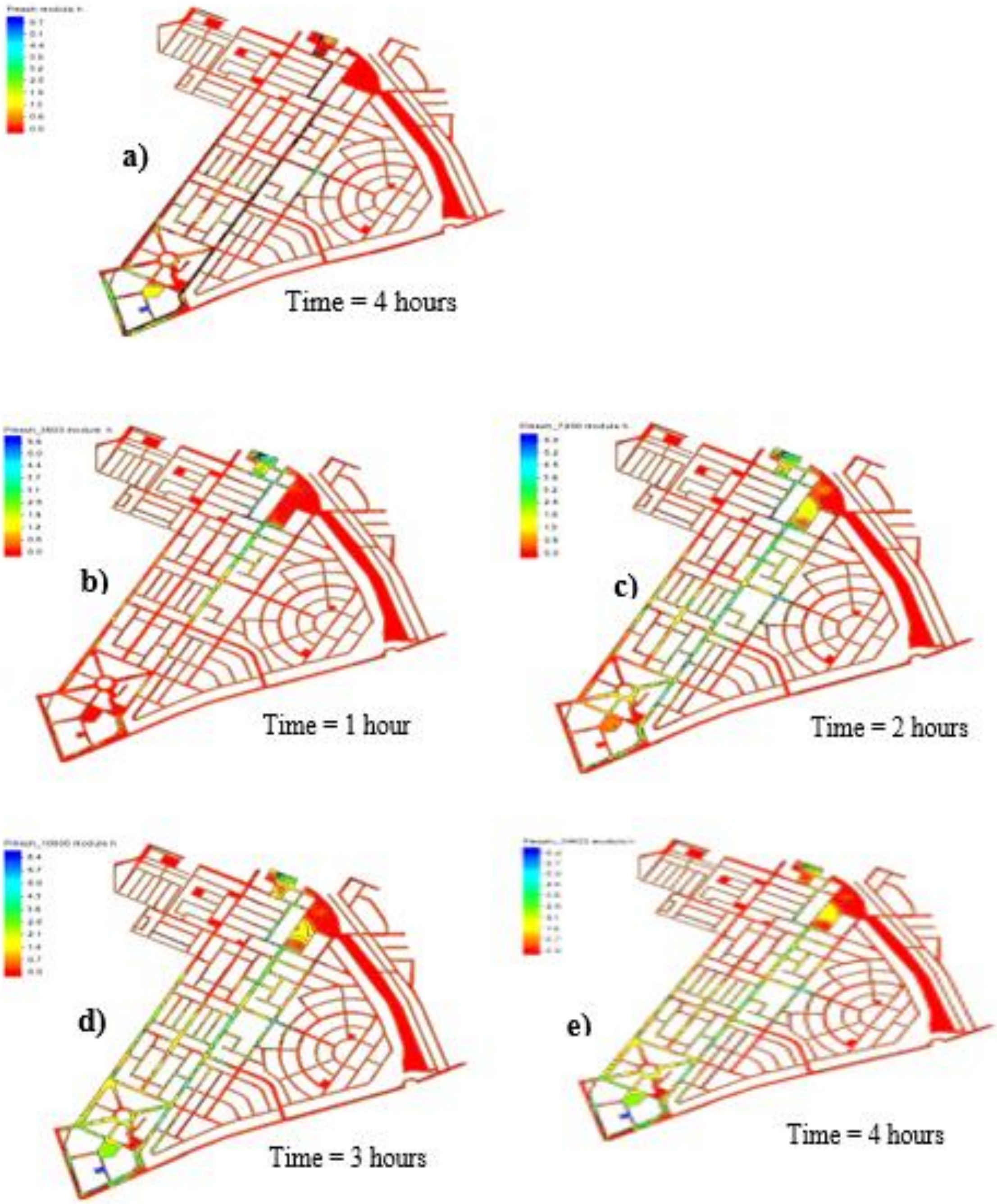

Figure 31 Maps interpolated of water depth by the fine 2D model and the porosity model of the Riviera palmaraie (Abidjan)

to problems involving flooding over complicated terrain (where ponds may form at different elevations). Although the fine 2D depths compared quite well with the porosity depths, further experiments are needed to verify. Overall, the water depths seem to be higher and they increase in croissant order with different times. Moreover, the maximum water depths obtained both at the upstream toward downstream part of the main area. However, there is an overestimation an underestimation of the upstream effects of inundated areas on Riviera Palmaraie and an underestimation of the downstream effects It is apparent that the water depths had an effect in the inundated areas. Figure 31 shows four figures which give a comparison of the computed free surface elevation marks with dz. The time series of free surface elevation for the 1, 2, 3, and 4 hours of spatial distribution rainfall demonstrates the capacity of the model to simulate hydraulic variables. The differences between the simulated free surface elevation are generally low, and the overall

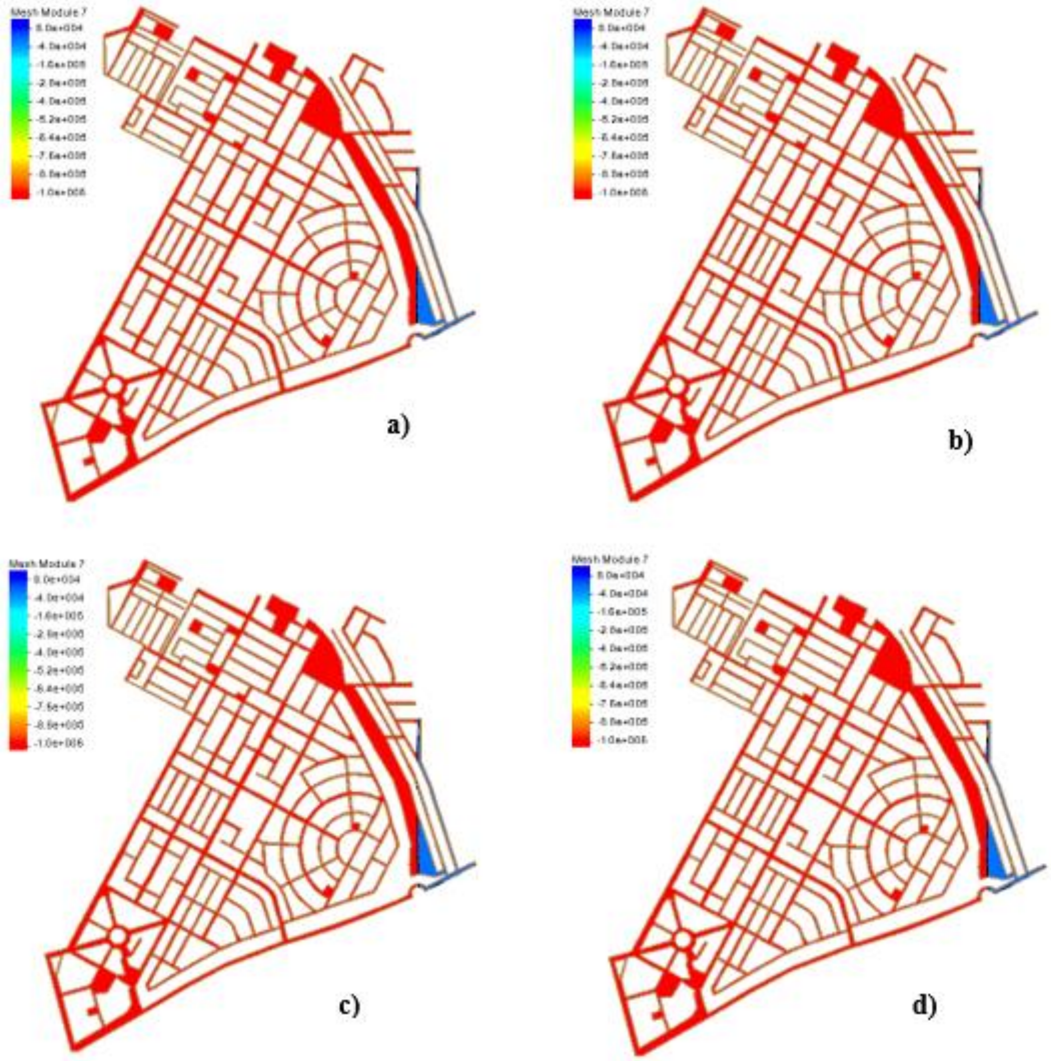

Figure 32 The difference comparison between the fine 2D model and the porosity model, showing spatial maps of free surface elevation marks with dz =Fmesh computed-Pmesh computed

They have the same appearance. The mean difference between the models is about a few centimeters. There is a low difference (up to 8 cm) between the results of different simulations (Figure 31). These differences confirm the importance of the roughness parameter in the floodplains of the area.

4.3 Flood map

The mapping of flood-prone areas is a fundamental element in the prevention of flood risks in order to define a sectorization of the flooded areas of the Riviera Palmaraie district of Abidjan. It is supposed to provide an estimate of the main flooding characteristics (heights, velocities, durations) associated with a return period at each point in space. In order to identify the flood-prone areas, we used Geographic Information Sciences (GIS) and, more particularly, QGIS software. To map the flood hazard, we adopted a broad definition that integrates the intensity of the phenomenon, i.e., flow heights and speeds.

The qualification of the hazard, low, medium, or high, depends on the intersection between these two parameters according to the grid giving table in Table 5, which reflects the fact that the higher the water height or flow velocity, the greater the danger. Based on the results of the model, a classification of the areas of the study area according to the simulated water heights and velocities of the flood of June 25, 2020 was made, allowing the distinction of 3 classes of hazard indicated as follows:

Table 5 Hazard grid selected-Crossing of heights and velocities

Velocity outflow (m/s) / Height of submersion (m)	V < 0.2	0.2 < V < 0.5	0.5 < V < 1	V >1
H < 0.2	Weak		Medium	
0.2 < H < 0.5	Medium			
0.5 < H < 1				High
H>1				

This hazard grid will make it possible to characterize the risk of river overflow and runoff at any point in the territory and to map it. It is the crossing of these hazard maps and the maps that will allow the construction of the regulatory zoning map.

Figure 33 Classification of flood zones according to the rainfall event of June 25, 2020

- Green zones: low risk zones (h < 0.2 m and v < 0.5 m/s)
- Yellow zones: moderate risk zones (0.2 < h < 0.5 m and v < 0.5 m/s)
- Red zones: high risk zones (h > 1 m and v > 1 m/s)

According to the results of the model, we can see that water overtopped the canal and occupies roads, the highly flood-prone areas are mainly located in the downstream and all along the street.

By evaluating this map, the high-risk areas identified correspond well to the areas observed in reality during and after the June 25, 2020 flood event. It can be estimated that one third of the areas where the risk is present are in the high flood zone and two thirds in the medium or low risk zone. we can say that flooding could occur only in case of heavy rainfall. Overall, the medium flood risk is dominant and corresponds to areas that have been developed to an acceptable level.

Although the human occupation of areas naturally favorable to flooding is a source of risk for their inhabitants, the risk of flooding and its manifestation are exacerbated by a number of factors that testify to the weakness of our society in managing urban space.

The first of these aggravating factors of floods in Abidjan is the inadequacy of the drainage network to the needs. Indeed, although Abidjan benefits from a large stormwater drainage network (some 1,200 km, not including that of most real estate operations), it does not meet the city's needs in terms of stormwater drainage everywhere. Not only have some gutters deteriorated over the years, but also, the recalibration of the existing network has not kept pace with urbanization. As a result, during heavy rains, most of the gutters, no longer able to channel the volumes of water that have become too large for their size, are saturated and overflow. The floods observed in Cocody (the best equipped commune), and more particularly in the Riviera Palmeraie, are largely due to this obsolescence of the drainage network. In spite of this, the infrastructure currently in place is often built under budgetary constraints, which significantly influences the technical choices made. Worse, when the open gutters overflow during heavy rains, they become dangerous for pedestrians and motorists. This is evidenced by the accidents that have occurred in the large sewer in the neighborhood.

The second factor concerns the malfunctioning of the existing drainage network due to the misuse of the gutters created for the evacuation of rainwater. In fact, in almost all working-class neighborhoods, in the absence of a wastewater drainage system, residents discharge their wastewater directly or through makeshift pipes into the gutters. In neighborhoods built on flat sites wastewater evacuated does not drain away, because of the low slopes which occurred stagnates water. Unfortunately, these rainwater drainage infrastructures are insufficiently maintained and blocked wastewater with various detritus, including sand, much of which is the result of soil erosion, most of the gutters cannot properly perform their function of evacuating rainwater. The consequence is the frequent flooding observed in many areas of Abidjan city, following the slightest rain.

4.4 Flood risk mitigation measures

Faced with frequent flooding and rapid urbanization of the city of Abidjan, the implementation of measures to mitigate this risk becomes necessary, we propose in this part some measures concerning the area studied:

- New development policies and application of texts regulating urban planning. Indeed, of all the factors aggravating natural hazards in the Abidjan area, the laxity of the public authorities could be considered as the most determining factor;
- The resizing of the drainage networks and especially those located around the roundabout of the street on the linear of the street;
- The sensitivity of the residents to avoid the obstruction of the drainage pipes by waste

and the implementation of regular cleaning and maintenance of the pipes;

- The limitation of the urbanization of the city which is done at the expense of the forest spaces which represent natural devices of protection;
- improvement of land use plans, by indicating more clearly on the master urban plans the natural hazards such as flooding in order not to build in dangerous areas. In this context, the preventive mapping of natural risks becomes an informative document in which all the knowledge on the different hazards of the locality can be integrated;
- The municipality should focus on more storage in the study area in order to retain water coming from upstream to avoid water to reach downstream where more frequent flooding is allowed;
- Reinforcement of the foundations of risky structures;
- Relocation of vulnerable properties;
- Improvement or implementation of protective structures;

All these measures aim at being prepared for such events and can therefore accelerate the recovery phase.

5 CONCLUSION

5.1 General Conclusion

This thesis provides a contemporary effective modeling approach based on 2D shallow water (SW) models with an innovative parameterization suitable to local and district-scale urban flood modeling. This master's thesis is based on the HydroSciences laboratory's new SW2D calculations code.

This model is based on the creation of a fine mesh of the research region, which was done satisfactorily in the first phase. In addition, the porosity model was created and validated for comparison. After comparing the findings of the two models, it was discovered that the porosity model's results did not fully match those of the fine 2D model. Some of the results suggest a mismatch between the fine and porosity models. The parameters of the porosity model should now be able to be adjusted using the fine model. The assumptions of two-dimensional tools, on the other hand, allow them to be used for a greater number of configurations, but they require more topographic data and time. It is rather tough to achieve good accuracy and a short calculation time in the outcomes. The porosity model will help us to overcome the obstacles that the fine model has already presented, particularly those relating to the surface of the research regions and the extremely short calculation time. The user of these various calculation routines must consequently choose between speed of execution and accuracy of results. High resolution topographic data, on the other hand, must be employed to assure accurate modeling and reasonable information loss.

The multiple porosity model, which is particularly suited for urban applications since it takes into account the favored flow paths along the streets, is another option. However, for the time being, the user must guess the porosity parameters of this model; I did not have time to test it.

These models allow for the more or less precise prediction of the spatial and temporal distribution of flood water levels and velocities in the second phase. The results then enable for the assessment of the anticipated flood's intensity, as well as the deduction of the likely repercussions on the population, economy, and environment, as well as the implementation of mitigation strategies.

From a forecasting standpoint, the models can be useful in the management phase of population evacuation and the targeted dispatch of relief supplies to the most vulnerable areas. This chapter starts with concluding remarks on the model, then moves onto the limitations of the thesis.

On the other hand, observations and findings are highlighted, some opportunities for further research and the chapter ends with recommendations.

5.2 Observations and findings

It is important to observe and document the flood behavior more. Things to observe would be how quickly the drainage channels fill, at what moment in time the capacity of the main channel is exceeded, where the water is held up, how deep the inundations are, in what areas they occur and along which paths the rainwater flows after hitting the ground. This general behavior of the flood needs to be documented, as it is usable for the validation, allowing for a comparison between model behavior and the documented flood behavior.

A possible method of observing would be using satellite images, but since the floods occur during heavy rainfall clouds can block the visibility. Other possibilities include aerial observations from airplanes and observations from the ground using people. If the choice is made for aerial or satellite observations it might be possible to combine the observations with the improvement of elevation data. In such a case a spatial resolution of at most 5 by 5 meters is recommended. For the best observation of the flood dynamics a temporal resolution in the tens of minutes is recommended (Liu et al., 2011).

We developed a fine mesh model and then the porosity model created in order to enables a significant reduction of the computational cost for urban flood modelling. This model makes possible the systematic analysis of the influence of building on inundation flow through the computation of the flow variables for a wide range of urban geometries. Finally, the impact of urbanization on future flood damage is analyzed.

5.3 Limitations

The models utilized in this study have some limitations. The fundamental flaw is that neither the fine nor the porosity models have been calibrated or validated. This is because of three major factors:

1. For lengthy periods of time, high resolution data is expensive and difficult to gather;
2. Floods occur infrequently, therefore measurement devices are unlikely to be in the correct location to record data.
3. Because there are no measurements to test the model's performance under various conditions, one can only presume that the results will be correct for greater discharges but not necessarily for lower discharge times. The findings of the model will be studied primarily for circumstances in which the model was originally calibrated, as this study focuses mostly on flooding periods.

   others limitations are more fundamental to the present research as follows:

- Few months are unquestionably insufficient to address all pressing problems on the thesis's topic while also leaving some restrictions or future work possibilities unaddressed.
- Validation of a conceptual model is a challenging undertaking that cannot be completed definitively until the final model is established.
- The lack of gauged data was one of the study's weaknesses. There are only a few rainfall stations in the area, no gauged data on outflows and water levels in the catchment, and no flood depths available in the metropolitan area. In a practical situation, this made it impossible to quantify the differences between the integrated forms of modeling.
- We did not investigate how different land use categories, such as parks and gardens, may be identified in the urban procedural model in this study. A spatial distribution of roughness coefficients and infiltration coefficients might improve the portrayal of urban areas in this way.
- It is advisable to utilize a longer simulation time to obtain a better estimate of the correlation of urban and local events and their impact on the flood risk in the urban area. The available period with precipitation data in this study was only one month, yet this may be insufficient to offer a reliable estimate of the return periods.

Another restriction to be stated is the author. Because this is a Master's thesis, the author's knowledge and experience are restricted. These constraints were overcome by discussing with the supervisor and relying on available literature.

5.4 Further research

A number of future research opportunities can be found in this thesis. The purpose of this thesis was to develop 2D model of fine and porosity for comparing adapted to urban district configuration, taking into account building effects on urban flood flow patterns. The application of the code, at an agglomeration scale for urban flood risk should be investigated along with the question of spatialized parameters calibration on existing datasets. The directives that were given for the improvement in data can be used to conceive and carry out a plan. There is also the possibility of narrowing down the requirements for the data, such as the exact resolution of data necessary to accurately simulate the flood dynamics.

An obvious opportunity and the next step, is to construct the model, calibrate and validate it. This will also allow for a conclusive validation of the model.

Moreover, the perspectives for improvements conducted in this research are presented in the following section.

First, we used depth-independent porosity parameters. This requires the treatment of the topographic information to identify the obstacles sufficiently high for not being overtopped by the flood. Özgen et al. (2016a, 2016b) derived recently a porosity model with depth-dependent porosity parameters but they only used their model to compute flows over low-level obstacles (micro-topography). It is of high interest to explore the possibility to reproduce the submersion of higher-level obstacles like buildings with such multiple porosity model, which is well suited for urban applications.

Although we highlight the potential benefit of distinguishing different porosity parameters for each term of the governing equations to reproduce optimally the impacts of the obstacles, it misses today a generalization of this approach for real-world application. To fill that gap, further work is needed to analyses the complex impact of the fine-scale obstacles on the coarse-scale flow field. The recent contribution by Guinot et al. (2017) paves the way in this direction, by distinguishing different porosity parameters for the advective terms of the governing equations in its dual integral porosity model.

Third, while the computation of inundation flow at a macro-scale was shown to reproduce the inundation water depths with a good level of accuracy, the complex distribution of the dynamic variables is poorly represented at this scale. This is more a limitation of the porosity model than a perspective for future improvements.

5.5 Recommendations

Based on this research findings from the 2D model a number of recommendations were derived.

- related to the data, the documented observations on flood dynamics and the resulting inundations were found insufficient and the available data was not as complete and accurate as necessary. It was recommended to improve both the observations and the measurements, and directives for doing so were given;
- concerned with the structure of the model and the simulation of the water flows. A cell-based, one-dimensional model structure was recommended due to applicability in situations with less accurate data sets and its flexibility;
- to assume a number of hydrologic processes as non-existent, namely the precipitation, evapotranspiration and infiltration. These processes are insignificant during the course of the flooding events in Riviera palmaraie;
- improve both the observations and the measurements;
- lead Local Flood Authorities reviewed the model results and compared them with their

local and historic knowledge;

- establish a continuous flood vulnerability index (FVI) monitoring system for the city of Abidjan to show a trend in the development of the area over time and also provide concrete information for flood preparedness.

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APPENDICES

Appendix A: File formats

A.1. Simulation input file

A.1.1. File structure

Line no	Variables
1, 2, 3	Comment lines (for user)
4	Simtyp, hot, hyp, dif, res, ori, prec, inf, exch, wind, pmp, gat, net
5, 6	Comment lines
7	g, D
8, 9	Comment lines
10	T0, Tmax, DtMax, DtMap, DtTim
11, 12	Comment lines
13	Schem, solv, NitMax, Eps, hmin, Crmax, Vmax, FrMax, div, NitDivMax, hstop
14, 15	Comment lines
16	Geometry file name (.geo file)
17, 18, 19	Comment lines
20	**u** or **U** if Boussinesq coefficient is uniform; **v** or **V** is Boussinesq coefficient is
21	Boussinesq coefficient (taken into account only if **u** or **U** in line 20)
22	Boussinesq coefficient file name (taken into account only if **v** or **V** in line 20)
23 – 25	Comment lines
26	**u** or **U** if porosity and Strickler are uniform; **v** or **V** is porosity and Strickler are non
27	Phi, K1, K2, ThetaK (taken into account only if **u** or **U** in line 20)
28	Hydraulic parameter file name (taken into account only if **v** or **V** in line 26)
29 – 31	Comment lines
32	**u** or **U** if singular head loss parameters are uniform; **v** or **V** if nonuniform
33	s1, s2, Alpha
34	Head loss parameter file name (taken into account only if **v** or **V** in line 32)
35 – 36	Comment lines
37	Name of orifice data file
38	Comment lines
41	**u** or **U** if rainfall station code is uniform; **v** or **V** otherwise
42	Rainfall code (taken into account only if **u** or **U** in line 41)
43	Name of the file for the rainfall station map
44 – 46	Comment lines
47	**u** or **U** if infiltration coefficient is uniform; **v** or **V** otherwise
48	Infiltration coefficient (taken into account only if **u** or **U** in line 47)
49	Name of the file for the infiltration coefficient map
50 – 52	Comment lines
53	**u** or **U** if building exchange parameters are uniform; **v** or **V** otherwise
54	Dzb, Kexch (taken into account only if **u** or **U** in line 53)
55	Name of the file for the building exchange parameters map
56 – 58	Comment lines
59	**u** or **U** if wind station code is uniform; **v** or **V** otherwise
60	Wind station code (taken into account only if **u** or **U** in line 59)
61	Name of the file for the wind station map
62 – 64	Comment lines
65	**u** or **U** if initial flow field (z, u, v) is uniform; **v** or **V** otherwise
66	z_{init}, u_{init}, v_{init} (taken into account only if **u** or **U** in line 65)
67	Name of the file for the initial conditions map
68 – 70	Comment lines
71	**u** or **U** if initial water depth in buildings is uniform; **v** or **V** otherwise
72	Etha init (taken into account only if **u** or **U** in line 71)
73	Name of the file for the initial conditions in buildings map
74 – 76	Comment lines
77	Name of the file for boundary conditions time series

78	Comment lines
79	Name of the file for the precipitation time series (if prec = 0, juste write a dummy string)
80, 81	Comment lines
82	Name of the file for the wind time series (if wind = 0, juste write a dummy string)
83, 84	Comment lines
85	Name of the pump data file
86, 87	Comment lines
88	Name of the gate data file
89, 90	Comment lines
91	Name of the network data file
92 – 94	Comment lines
95	Name of the binary result file (map variables, storage period DtMap)
96	Name of the time series file (storage period DtTim)
97	Name of the boundary flux file (storage period DtTim)
98	Name of orifice output file (storage period DtTim)
99	Name of pump output file (storage period DtTim)
100	Name of gate output file (storage period DtTim)
101	Name of drainage network outpu file (storage period DtTim)
102	Name of trace file
103 – 105	Comment lines
106	Flags for storage of h, z, unit discharges, velocities, Fr, Cr (storage period DtMap)
107, 108	Comment lines
109	Flags for map storage of Etha, Hs, Ht (storage period DtMap)
110 – 112	Comment lines
113	Flag for calculation of discharge through pre-defined sections (0 or 1)
114	Name of section definition file
115	Name of section discharge output file
116, 117	Comment lines
118	Number of time series storage points (storage period DtTim)
119 – end	For each storage point: x and y

A.1.2. Meaning of the variables

Variable	Type	Unit	Meaning
Alpha	R*8	rad	Angle of principal direction 1 with the x axis
CrMax	R*8	–	Maximum allowed Courant number for stability. Only values smaller than 1 are taken into account
D	R*8 (double)	$m^2\ s^{-1}$	Diffusion coefficient. Active only if dif = 1
dif	I	–	0 : no diffusion ; 1: diffusion is activated
div	I	–	0 : no divergence correction 1 : divergence correction activated If div = 1 please set hstop to 0
DtMap	R*8	s	Time step for the storage of 2D maps
DtMax	R*8	s	Maximum time step fixed by the user
DtTim	R*8	s	Time step for the storage of time series at fixed points
Dzb	R*8	m	Elevation of building basement relative to ground (positive is building basement is above ground level, negative if building basement is below ground level)
Eps	R*8	–	Relative convergence criterion for conjugate gradients (diffusion step, only if dif = 1)
Etha Init	R*8	m	Initial water depth in the basement of the buildings
FrMax	R*8	–	Maximum Froude number allowed by the user (if Fr is larger, the velocities will be reduced so that Fr = FrMax)

g	R*8	m s^{-2}	Gravitational acceleration
gat	I	–	0: no controlled gates 1: gates handled via 1st-order time splitting
hmin	R*8	m	Water depth under which the fluxes with the neighbour cells are assumed zero
hstop	I	–	0 : computations continue in case of negative depths 1: computations are stopped in case of negative depths

K1	R*8	m$^{1/3}$ s^{-1}	Strickler coefficient in principal direction 1
K2	R*8	m$^{1/3}$ s^{-1}	Strickler coefficient in principal direction 2
kexch	R*8	–	Exchange coefficient between buildings and overland flow
net	I	–	Flag for drainage network model
NitMax	I	–	Maximum number of iterations for conjugate gradients (only if dif = 1)
NitDivMax	I	–	Maximum number of iterations in the Divergence Correction routine
ori	I	–	1: Orifices handled via 1st-order time splitting 2: orifices handled via 2nd-order time splitting
Phi	R*8	–	Porosity
res	I	–	0: no friction 1: time splitting + analytical solution over the time step 2: time splitting + explicit Euler
s1	R*8	–	Singular head loss coefficient in principal direction 1
s2	R*8	–	Singlura head loss coefficient in principal direction 2
scheme	Char*2 (between	–	‘g’ : Godunov ‘m1’ MUSCL-EVR
solv	I	–	1 : HLL with porosity 2: HLLC with porosity (Guinot & Soares-Frazao 2006) 22: HLLM (Guinot 2010) 3 : ApStat (Lhomme & Guinot 2007)
T0	R*8	s	Simulation begin time
ThetaK	R*8	rad	Angle of Strickler principal direction 1 with the x axis
Tmax	R*8	s	Simulation end time
uinit	R*8	m s^{-1}	Initial flow velocity in the x direction
vinit	R*8	m s^{-1}	Initial flow velocity in the y direction
Vmax	R*8	m s^{-1}	Maximum flow velocity allowed by the user (velocities larger than Vmax are “clipped” to Vmax)
zinit	R*8	m	Initial water level

A.2. Extract file format

Line	Content
1, 2	2 comment lines
3	Name of geometry file
4	Name of simulation result file
5	Depth threshold value for extraction
6, 7	2 comment lines
8	Number N of maps to be extracted
9 to N + 8	t, var, file name, code
End of file	--> Max, etc. **Do not remove these lines**

t : Time for which the variables are to be extracted var : Variable code (see Table 3.2)

file name : name of the text file where the map is to be extracted. **Between quotes (')**

code : interpolation code, between quotes. **Use 'c**

A.3. Sample files

A.3.1. fine model simulation file

```
Input file for SW2D 1.1d
==================================================================
simtyp hot   hyp   dif res   ori  prec        inf          exch
 1     0     2     0   1     0                0              0         0
--
wind       pmp        gat        net        zbv
0             0       0          0          0
--
  g    D    CoefWind
9.81   0.   0.
--
T0         Tmax       DtMax      DtMap                 DtTim
0.         14400.     2.         1800.                 300.
--
schem      solv       Nitmx      Eps        hmin       CrMax      Vmax       FrMax      div        Ndvmx      hstop
'g'           1       1          0.         1d-5       1.         1000.      2000.      0          10         0
============================================================
Geometry file, flag for period BC, file name
../Fmesh.geo
0
No periodic BC
============================================================
Boussinesq PhiW PhiG Etax Etay (only if hyp=1 or hyp=2)
Distribution type, File name
u
1.         1.         1.         0.         0.
No distributed Boussinesq & porosity file
============================================================
Porosity for hyp = 3 (will override the above params)
Number of tabulation levels for Phi_Omega and Phi_Gamma
5          5
--
Law type, parameters for PhiW
u
3    8.619    8.689    8.852    8.875    9.156
Mesh_05-12_phiW.in
--
Law type, parameters for PhiG
u
3          8.8629    8.956    8.965   8.970    10.683
Mesh_05-12_phiG.in
============================================================
MP model (hyp = 4): distribution type, params, file name
Phim       Phis       Phi1       Theta1     Phi2       Theta2
u
0.1        0.1        0.1        0.                    0.1        90.
No porosity file
--
Exchange coefficients: distrubution, params, file name
X_ms       X_m1       X_m2       X_s1       X_s2       X_12
u
0.         0.         0.         0.         0.         0.
No file
============================================================
TP model (hyp = 5): PhiW, Phiq1 Phiq2 alphaq Phip1 Phip2 Alphap
Distribution type, File name
u
```

```
0.75          .181   .735   -10.6          .181   .735   -10.6
No file
=============================================================
Strickler
Distribution type, Values (K1, K2, Alpha), File name
u
60.    60.    0.
No file
=============================================================
Head loss parameters
Distribution type, Values (s1, s2, Alpha), File name
u
0.     0.     0.     0.
No singular head loss file
=============================================================
Orifice parameters
No orifice file
=============================================================
Precipitation codes
Distribution type, Value (code), File name
u
1
No precipitation file
=============================================================
Infiltration coefficient
Distribution type, Value (infiltr. coeff.), File name
u
0.
No infiltration file
=============================================================
Surface/buildings exchange parameters
Distribution type, Values (Dzb, Phi, kexch), File name
u
0.     0.     0.
No exchange parameter file
=============================================================
Wind codes
Distribution type, Value (code), File name
u
1
No wind file
=============================================================
Initial conditions surface
Distribution type, Values (z, u, v), File name
z
0      0.     0.
No file
=============================================================
Initial conditions buildings
Distribution type, Values (h), File name
u
0.
No file
=============================================================
Boundary conditions time series
../Fmesh.lim
=============================================================
Precipitation time series
../PrecTimeSerie.txt
=============================================================
Wind time series
```

No time series file
===
Pump data file
No pump file used
===
Gate data file
No Gate File
===
Network data file
No network file
===
Variable zb data file
No zb file
===
Output file names
Res (binary), Tseries, Boundary fluxes, Orifice fluxes, PumpQ, Trace file
../Fmesh.res
../Fmesh_Tim.txt
../Fmesh_BC.txt
No orifice file
No pump file
No gate file
No network file.txt
../Fmesh_Tr.txt
===
Flag for result storage

h	z	q	Eta	Theta	u	Fr	Cr	Hs	Ht
1	1	1	0	0	1	1	0	0	0

===
Interface storage flag (0/1)
and definition file for interfaces, result file
0
No sections input file
No sections output file
===
No time series points and for each: x,y
3
394341 594171 # ministre amont au lieu de 394334 594174, hors du maillage
393394 592923 # rosier aval
393452 592543 # confluence
=================
end of file

A.3.2. Extract file

A.3.2.1. Fine model extract file

```
Result extraction file
Geometry Binary results file name, hmin
Fmesh.geo
Fmesh.res
0.001
--
Nb of  dates and for each: t, Var Type, Outfile (between quotes)
2
14400.  1   'Fmes_h_14400.txt'   'c'
14400.  2   'Fmes_z_14400.txt'   'c'

-->Max
number of max
0
-->Sub
number of sub
0
-->Sur
Number of subsurf
0
-->Tim
Number of tim
0
```

A.3.2.2. Porosity model extract file

```
Result extraction file
Geometry Binary results file name, hmin
Pmesh.geo
Pmesh.res
0.001
--
Nb of  dates and for each: t, Var Type, Outfile (between quotes)
5
0.      2   'Pmesh_0_z.txt'  'c'
3600.   1   'Pmesh_3600_h.txt'   'c'
7200.   1   'Pmesh_7200_h.txt'   'c'
10800.  1   'Pmesh_10800_h.txt'  'c'
14400.  1   'Pmesh_14400_h.txt'  'c'

-->Max
number of max
0
-->Sub
number of sub
0
-->Sur
Number of subsurf
0
-->Tim
Number of tim
0
```

A.3.2.3. Simulation specifications

File name	Content	Format
Fmesh.2dm (supplied)	Computational mesh (meshing method#1)	Text
Fmesh.map (supplied)	Auxiliary file for mesh generator	Text
Fmesh .materials (supplied)	Auxiliary file for mesh generator	Text
Fmesh.sms (supplied)	SMS project file for Mesh#1	Text
2d_Mod01.in	Simulation file	Text
Fmesh.lim (to create)	Boundary conditions as functions of time	Text
Fmesh .bc (to create)	Boundary codes for Mesh#1	Text
Fmesh.geo (to generate)	Geometry file	binary
Fmesh..res (to generate)	Result file	binary
Ex.in (supplied)	Extract file	Text

Table 6 shows the names of the various files supplied and used in the present simulation.

```
==============================================================
Flag for result storage
h       z       q       Eta     Theta           u       Fr      Cr      Hs      Ht
1       1       1       0       0                   1   1       0       0       0
==============================================================
```

Figure 34 Result storage specifications

```
--
T0       Tmax     DtMax    DtMap              DtTim
0.       14400.   2.       1800.              300.
--
```

Figure 35 File 2d_Fmesh.in. View of the time step specification parameters

Appendix B: The SW2D modelling suite

Model description

Shallow Water 2 Dimensions (SW2D) is an acronym for shallow water in two dimensions (the package solves the 2D shallow water equations, another name for the 2D Saint Venant equations). This modelling suite has been under constant development at HydroSciences Montpellier since 2002. The package incorporates several engineering and research versions. It is used by four consultancy companies (Ginger/Grontmij, Cereg Ingenierie, Citeo, and Ameten). The software suite is made up of numerous executables that must be run in order (Figure 1). There are two elements to each executable name. The application's name comes first, followed by the version number. Ex27d.exe is the 2.7d version of the executable "ex," which is the application that extracts the results from the result files.

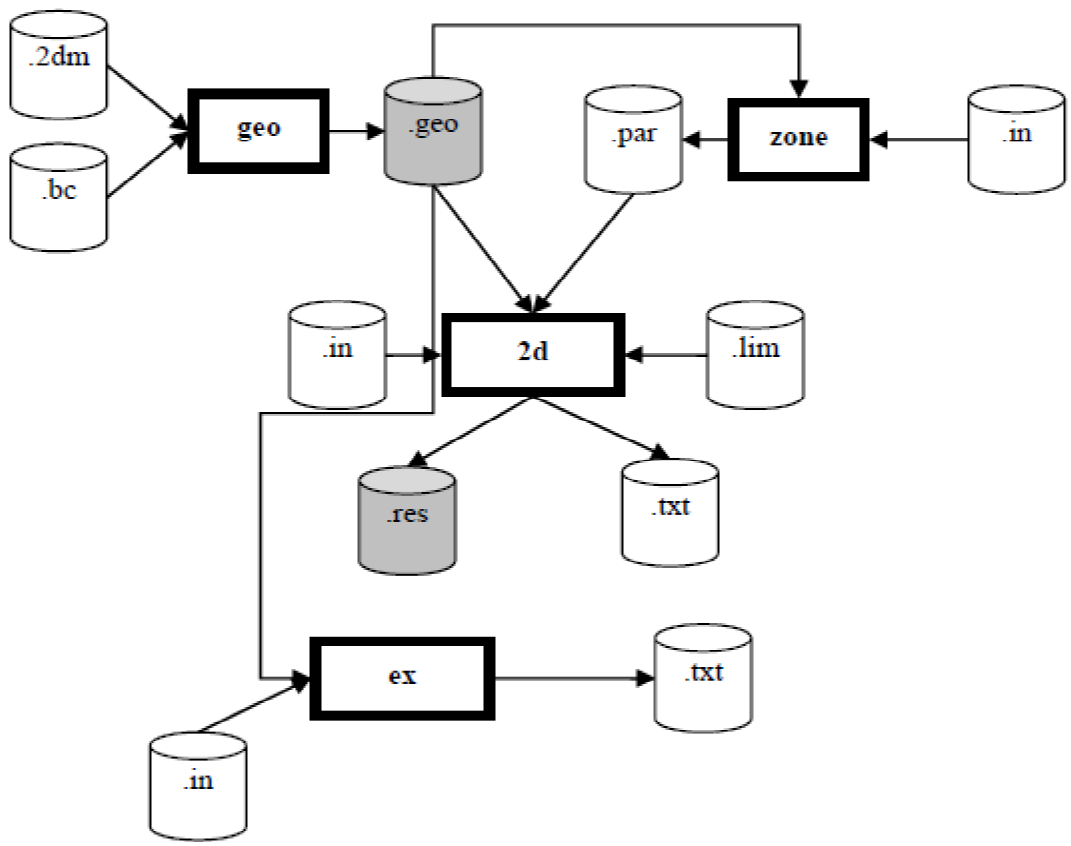

Figure 36 The SW2D modelling suite. Bold rectangles: executables. White cylinders: text (input/output) files. Grey cylinders: binary (input/output) files (Vincent Guinot et al).

The sequence as follows:

1) Analyze and process the geometric data using the geo executable. Geo takes the mesh file and the boundary conditions specification file and processes them to determine things like which cells

are neighbors, what their areas are, how long their interfaces are, and so on. The 2D executable creates a binary geometry file that is later used by the 2D executable.
2) Create distributed parameter files with the zone executable if necessary. If, for example, the Strickler's friction coefficient is spatially variable but piecewise constant over the domain, this could be the case. Zone makes use of the geometry file and necessitates the use of geo first.

3) The simulation engine is the second executable. It uses a finite volume technique to solve the 2D equations provided in Chapter 3. It can replicate static or moving hydraulic jumps, moving bores, trans critical flow, and so on without having to worry about mass or momentum conservation. Maps, which are saved at regular (user-specified) intervals into a binary file (the.res file in Figure B.1), and time series are the two major types of output (stored into text files). 4) The ex program extracts the results from the.res binary file. It generates.txt files that the SMS mesh creation software may display. A number of input data files were required to run the various SW2D modules. The model gardening has a mathematical aspect to it, and then there is input data, which is the geometry of the urban area and topography information, which is then combined and put into the model, which is then run through a simulation, and the outcomes are then analyzed. The structure of these files is covered in the next appendix.

Appendix C: Simulation process

C.1 Preparation of the Data

To use the SW2D model, the data needed must be formatted with the help of a GIS program. To use it, one must have the GIS data pre-formatted:

C.1.1 Topography

Grid files (.2dm), known as regular DEM, are the most current files used to define landscape topography (Digital Elevation Model). They are always composed of a header and a body and can be read in a text editor as block notes. The software can access the cell size, grid size (in lines and columns), and low left corner coordinates of the height map in the header (note: these coordinates correspond to the corner and not the center of the pixel). The elevation of each pixel on the map is displayed in the body section. If the user dislikes the format, he can convert the files to 2dm files using SMS software. The cell size, grid size (in lines and columns), and low left corner coordinates of the height map are all accessible to the application in the header (note: these coordinates correspond to the corner and not the center of the pixel). The elevation of each pixel on the map will be found in the body. If the format is unacceptable to the user, he can convert the files to 2DM files using SMS software. The following files are in shapefile (.shp) format.

An object component and an information portion make up the corresponding data for that file type (as they do for any file that comes from GIS software). Polygons (building delimitation, regions...), lines (road network, gas network...), and points are examples of geo-referenced geometric formations (GPS points, fire light position...). Information is stored in a table for each object, which is linked by a unique ID. The number of rows will be equal to the number of objects. In addition, the data is accompanied by a file containing the geographical projection. During file import, the software will read the coordinate system directly.

C.1.2 Code simulation

C.1.2.1 Operation sequence

```
C:\WINDOWS\system32\cmd.exe

D:\PAUWES\THESIS FILE\SWE TUTO\execute data\model fin\Simulation>SW2D_IP_11d.exe
 Calling INIT
 Input file name ?
../Fmesh.in
 Reading simulation parameters
 Simulation parameters checked and OK
   Boussinesq & porosity u
   Variable porosity parameters W  u
   Variable porosity parameters G  u
   Porosities     u
   Exchange parameters     u
   Tensor Porosity parameters  u
   Hydraulic parameters    u
   Hydraulic parameters 2 u
   reading orifice file
   Precipitation codes     u
   Infiltration parameter u
   Exchange parameters     u
   Wind parameters     u
   Initial condition       z
   Initial condition 2     u
   Reading BC time series file name
   Reading Prec time series file name
   Reading Wind time series file name
   Reading Pump data file name
   Reading Gate data file name
   Reading Network data file name
   Reading variable zb file name
   Reading output file names
               Track file../Fmesh_Tr.txt
   Reading storage flags
   Reading Interface storage flags
   Reading Drogue storage flags
 Input file read
 Reading geometry
 File opened
   Cells:            160787
   Interfaces:       335842
   Nodes      :      174922
   Cell area and gravity centre...
   Interface properties...
   assigning z1 and z2...
    ... done
```

Figure 37 running simulation process

0.3951949887E+06	0.5933387392E+06	0.0000000000E+00
0.3951956829E+06	0.5933368609E+06	0.0000000000E+00
0.3951963767E+06	0.5933349822E+06	0.0000000000E+00
0.3951970712E+06	0.5933331038E+06	0.0000000000E+00
0.3951977652E+06	0.5933312252E+06	0.0000000000E+00
0.3951984594E+06	0.5933293468E+06	0.0000000000E+00
0.3951991532E+06	0.5933274682E+06	0.0000000000E+00
0.3951923122E+06	0.5933375021E+06	0.0000000000E+00
0.3951930227E+06	0.5933356095E+06	0.0000000000E+00
0.3951937333E+06	0.5933337174E+06	0.0000000000E+00
0.3951944438E+06	0.5933318247E+06	0.0000000000E+00
0.3951951548E+06	0.5933299323E+06	0.0000000000E+00
0.3951958654E+06	0.5933280400E+06	0.0000000000E+00
0.3951965763E+06	0.5933261478E+06	0.0000000000E+00
0.3951896879E+06	0.5933362892E+06	0.0000000000E+00
0.3951904144E+06	0.5933343831E+06	0.0000000000E+00
0.3951911412E+06	0.5933324771E+06	0.0000000000E+00
0.3951918683E+06	0.5933305709E+06	0.0000000000E+00
0.3951925952E+06	0.5933286646E+06	0.0000000000E+00
0.3951933223E+06	0.5933267589E+06	0.0000000000E+00
0.3951940493E+06	0.5933248530E+06	0.0000000000E+00
0.3951871148E+06	0.5933351001E+06	0.0000000000E+00
0.3951878579E+06	0.5933331809E+06	0.0000000000E+00

Figure 38 The first 23 lines of the file extraction maps

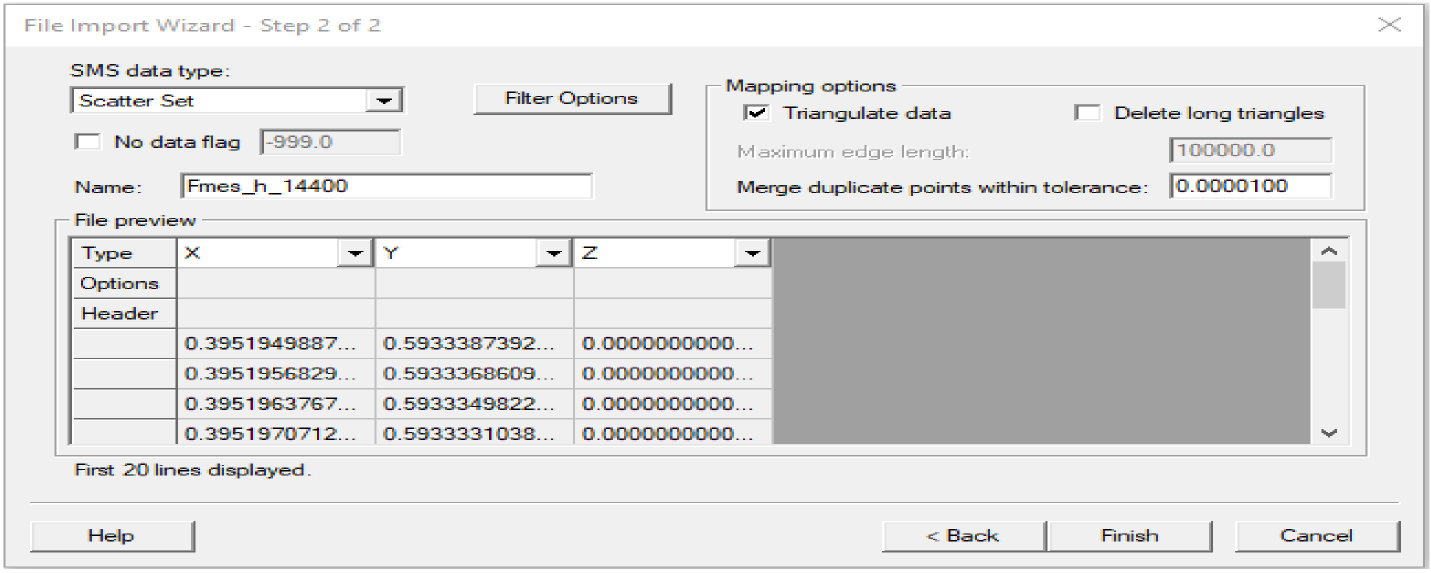

Figure 39 Importing vector data

A new data set is now visible in the project management window. The vector field visible on the screen of visualization default settings (figure C).

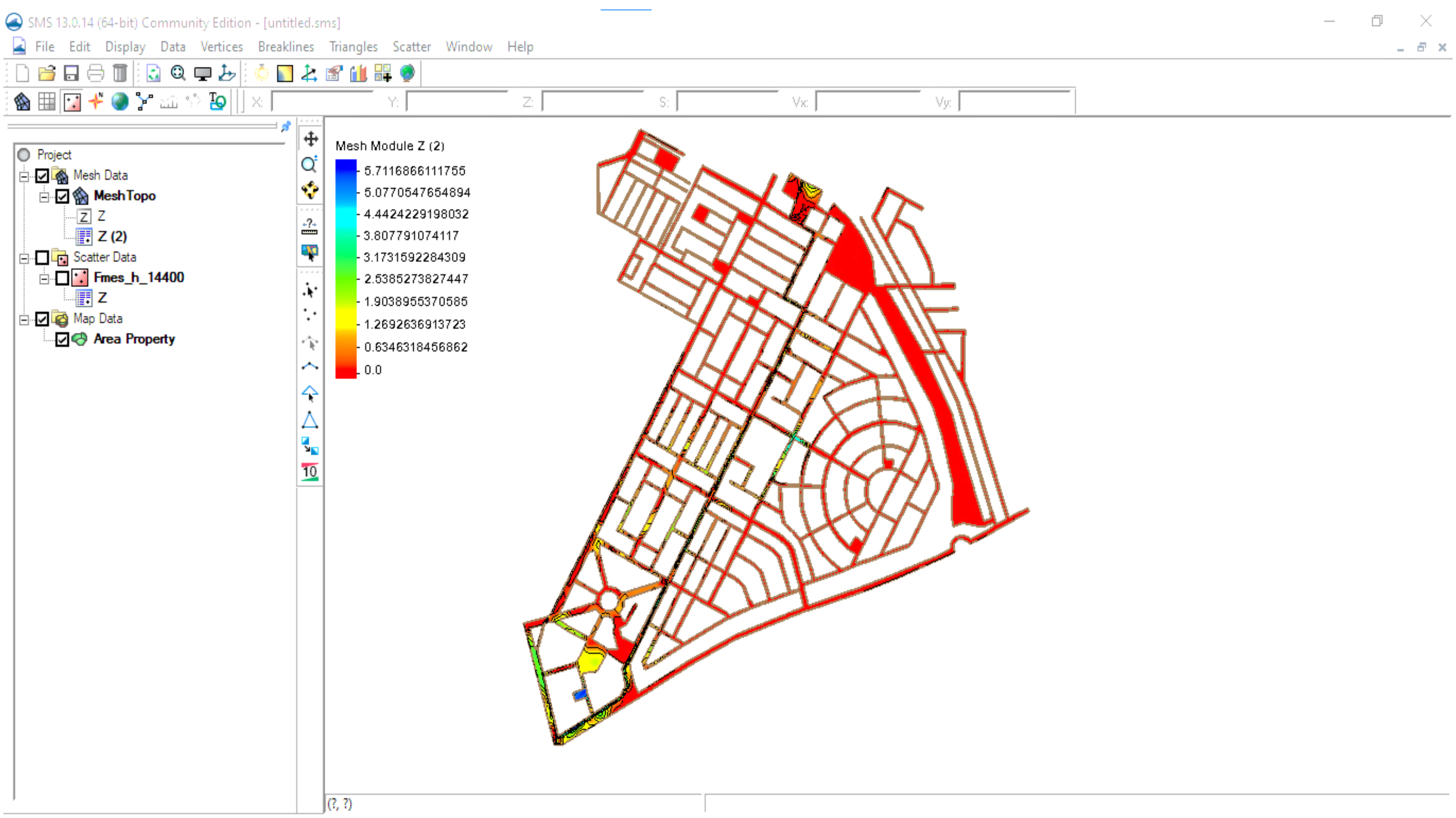

Figure 40 Displaying map (mesh-interpolated water depth map)

Appendix D: rainfall data measure

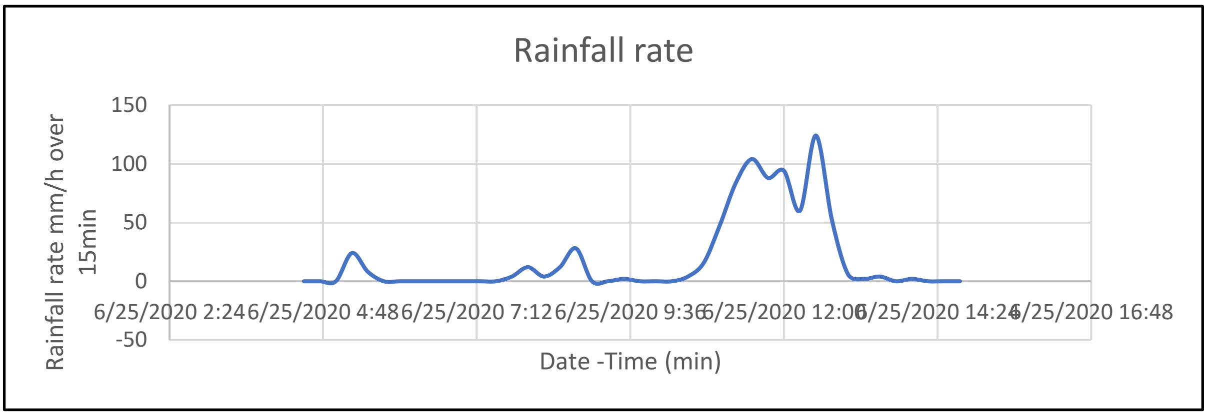

Figure 41 Rainfall intensity measured at the Centre F12 station during the 25th June 2020 flood event occurred in Riviera palmaraie

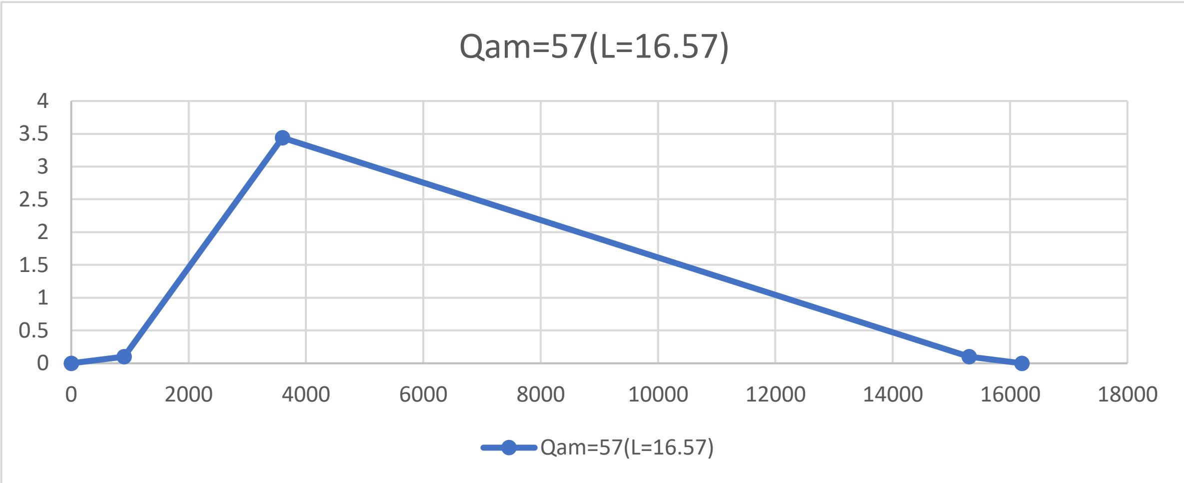

Figure 42 max flow rate

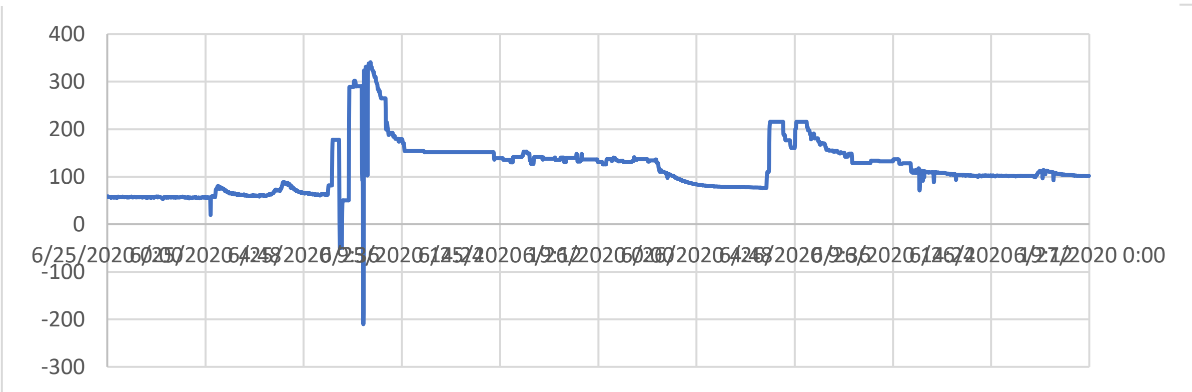

Figure 43 Estimation of the max flow rate by surface velocity measurement in the channel and the major bed: 67 m3/s