UCLouvain

École polytechnique de Louvain

Master thesis - Towards a better use of rainwater in urban areas through quantitative assessments of water flows – application to the Espierres watershed

Author: **Jade LORIAU**
Supervisor: **Sandra SOARES FRAZAO**
Readers: **Thais DELFORTRIE, Chiara CAVALIERI, Charles RYCKMANS**
Academic year 2022–2023
Master [120] in Civil Engineering

Acknowledgments

Before I get into the heart of the matter, I want to thank everyone who has contributed to this work.

The first person I want to thank is my promoter Sandra Soares-Frazao. She was able to motivate me and give me new leads while being very available throughout the year.

Then, I would like to thank Thais Delfortrie who trusted me to put her doctoral work into modeling, and for the help with the beginning of my thesis.

I would also like to thank Charles Ryckmans and Chiara Cavialeri for agreeing to be my readers.

I wish to thank all my friends who were present during these studies and who were able to motivate me when necessary. Especially Mathieu Deridder who read this work and gave me valuable advices.

Finally, I would like to thank my family. First of all, my parents who always supported me during these 5 years of study. Then my grandmother, who proofread and corrected my work.

Summary

The number of urbanized cities is increasing in the world. This urbanization raise concerns in several areas, specifically during major rain events. Urbanization and especially imperviousness prevents the rain from infiltrating and causes floods like those of July 2021.

In addition, natural water resources on earth are limited. Water stress is increasing in most countries. In particular cases, such as Belgium, it would be possible to avoid this water stress by filling the water tables with rainwater.

The aim of this graduation study is to improve the use of rainwater in the urban environment. On the one hand, reduce runoff on urban areas, and on the other hand avoid flooding due to sewer overflows. To do this, simulations at two different sites have been carried out on the SWMM software which allows to represent an urban area and its flows.

This work highlights the approach to be taken for modeling urban areas on the SWMM software and flow mitigation measures on various terrains under various rain conditions. It shows that depending on the catchment, the size and the duration of the rain, the choice of the mitigations solutions is really different. Also, private and public domain should be more studied before the construction of a new residential area. Some guidelines can be implemented in the private domain in order to decrease the runoff.

Contents

1 Introduction **6**
1.1 Floods and water stress in the World and in Belgium 6
1.2 Mitigation of floods in urban and non urban area 19

2 State of art **24**
2.1 Hydrological cycle 24
2.2 Hydrological modeling of urban areas 29
2.3 Zoom on SWMM 34

3 Hydrological modeling of urban area with SWMM **36**
3.1 Introduction 36
3.2 Representation of the system 37
3.3 Running a simulation 43

4 Study of the Espierres watershed **47**
4.1 Site history 47
4.2 Zoom on some particular places 49
4.3 Modeling steps 51
4.4 Proposed solutions and outcomes 67
4.4.1 Rue du Nouveau Monde 67
4.4.2 Ferme de la Blommerie 87

Conclusion **92**

A Cross section for conduits **96**

B SCS curve numbers **97**

C Runoff coefficient **98**

D Manning coefficient **100**

E IDF **102**

Whole bibliography **104**

Chapter 1: Introduction

1.1 Floods and water stress in the World and in Belgium

In the World, the number of natural disasters has increased a lot during the 20^{th} century [1]. However, in the 21^{st} century, the frequency of the disasters tends to be stabilized. We clearly see that the floods are the main disasters in number. Another important disaster is the extreme weather.

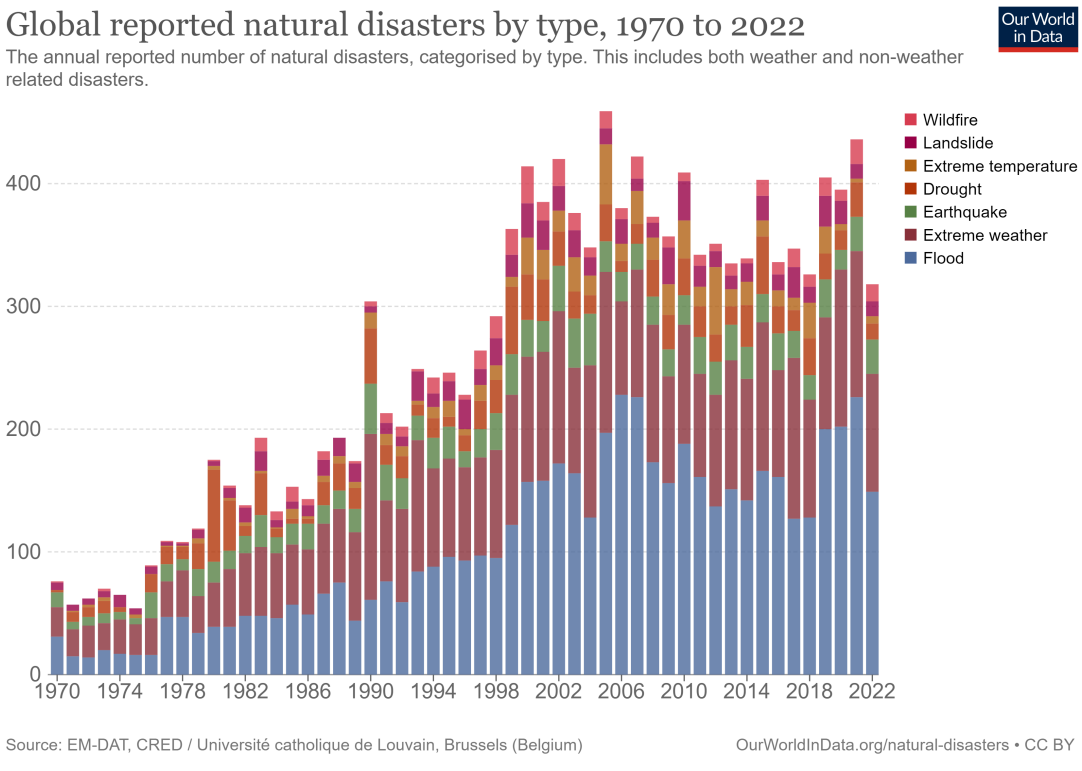


Figure 1.1: Natural disasters. [22]

[1] All the data of this section comes from OurWorldInData [22]

Although, the number of natural disasters tends to increase, the number of deaths from these disasters had decreased a lot. This tendency comes from all the mitigation process implemented in order to decrease the impact of these natural disasters. A lot of people can now be saved from these natural disasters.

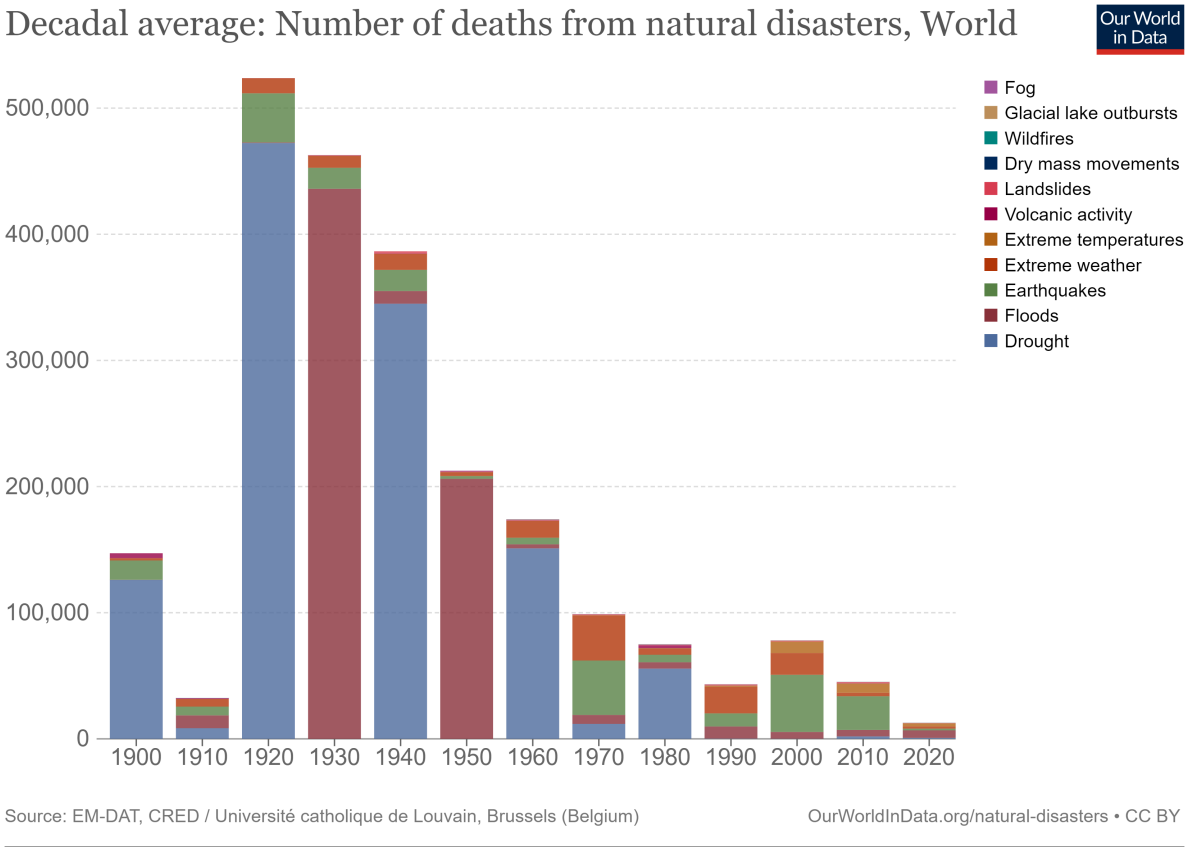


Figure 1.2: Decadal average of deaths from natural disasters. [22]

Now, another important aspect to consider is the economic impact. We clearly see that economic loss increases through years. Indeed, it can be explained by the cost of the buildings and the number of buildings affected because even if people don't die, they can be affected and the house where they live are also affected. Houses don't necessarily need to be destroyed, but have to be rebuild. As the number of disasters increases, the total number of people affected increases, so the economic loss increases too.

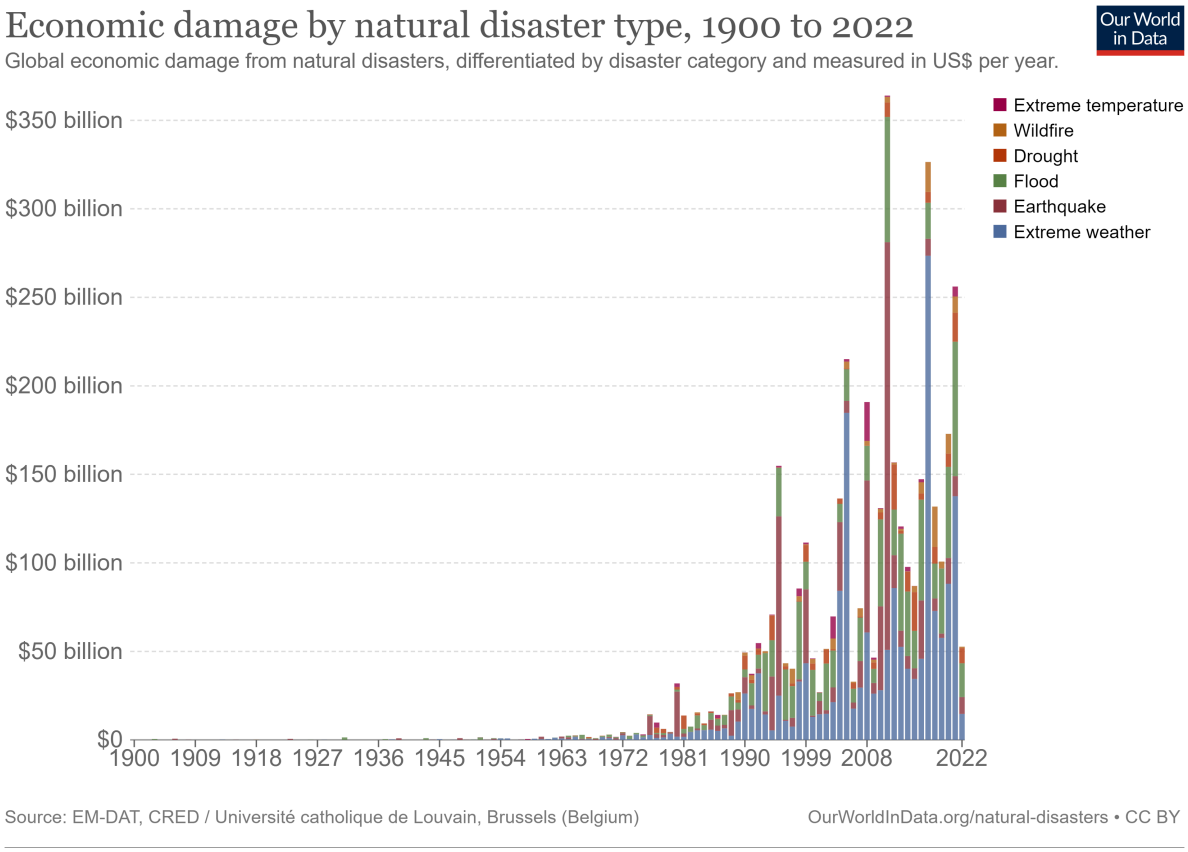


Figure 1.3: Economic damage due to natural disasters. [22]

Seen this tendency, it is important to try to limit the impact of the increasing natural disasters on the society, mitigating some catastrophes that can be attenuated or putting some solution in case of these tragedies happening.

My work will focus on the floods and the purpose is to propose some mitigation of floods in some particular case. Here are presented more in detail the statistics about the floods.

The number of floods in the World increases, in 2021 the number of events of floods reached 226. This is a general tendency in terms of natural disasters and floods don't escape to this constant increase.

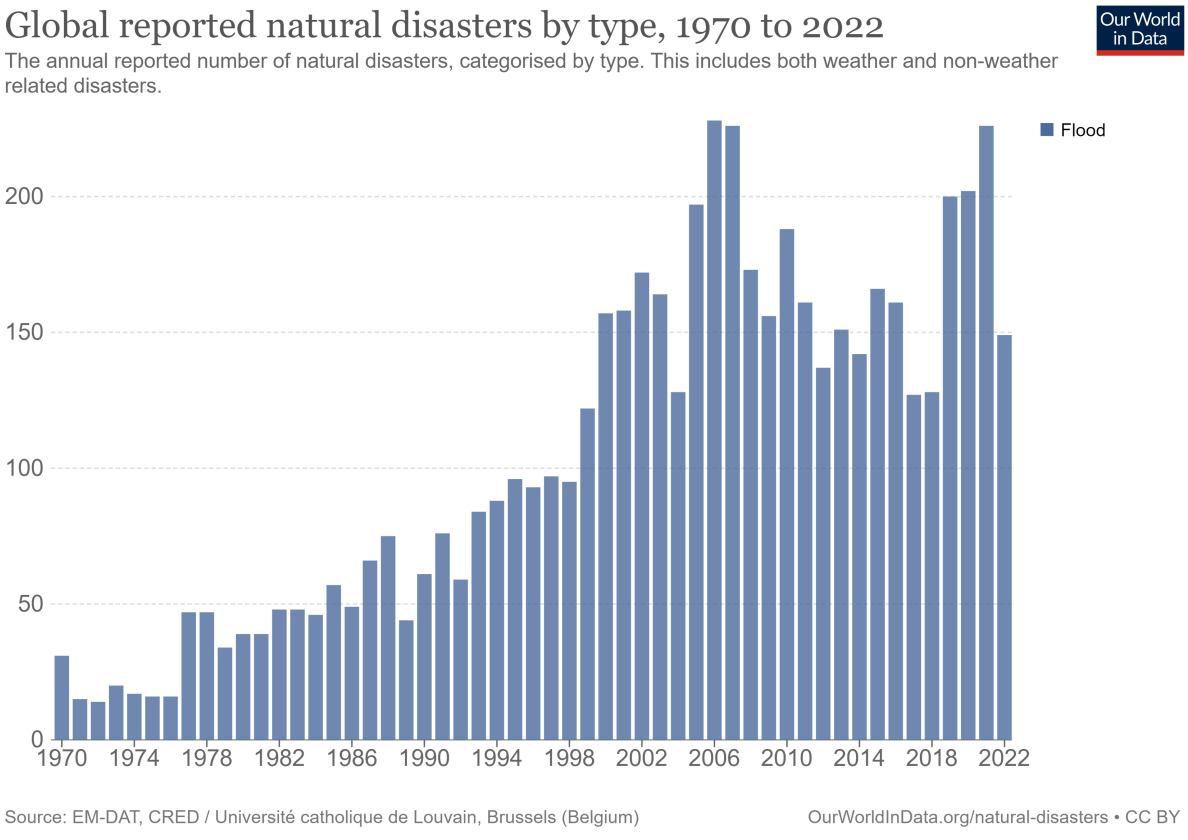


Figure 1.4: Number of floods. [22]

In the 2020 decade, the number of deaths fell to 5900 people compared to the 1930 decade with 436.150 people. However, the number of people affected had a peak in the 1990 decade and slowly decreased reaching the actual decade with a number of people affected similar to these on the surroundings of 1980. That means that some mitigations have been implemented and are useful.

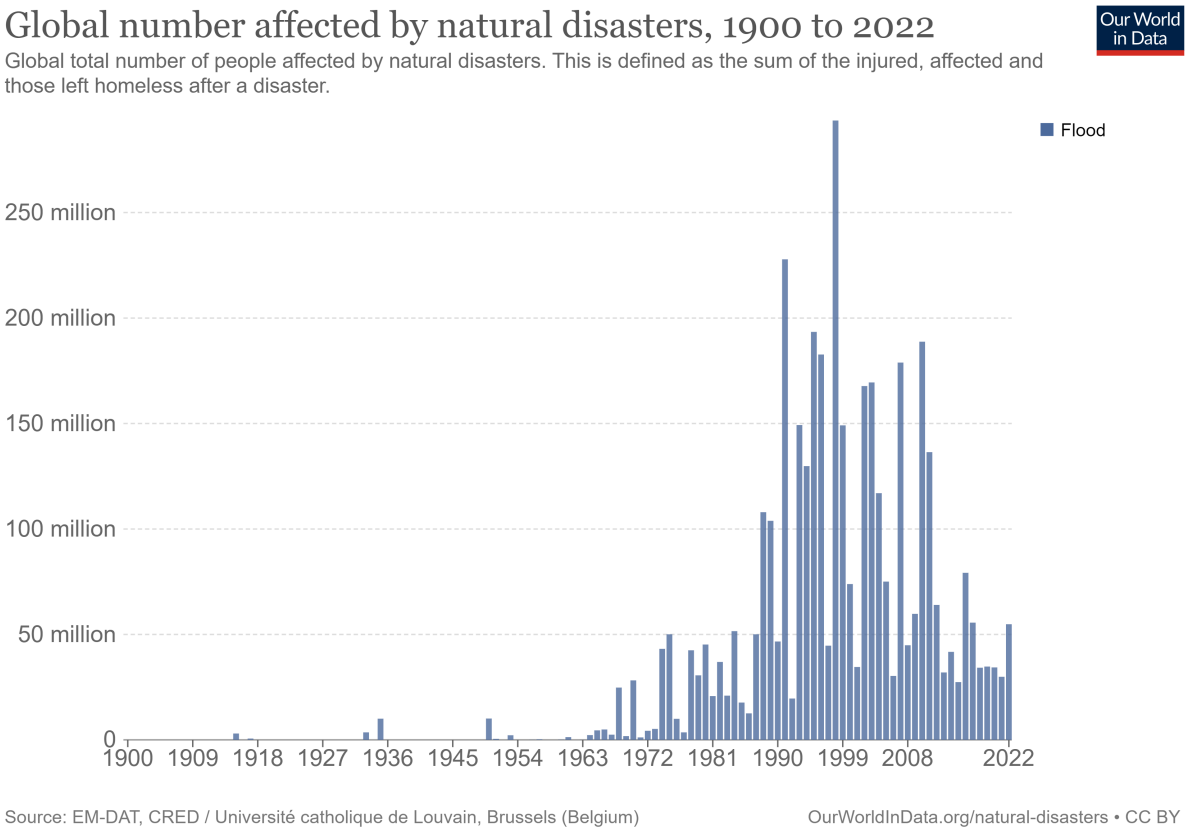


Figure 1.5: Number people affected by floods. [22]

Only the economic loss tends to increase, it doesn't seem to stabilize. The last episode of big flooding in 2021 costed 75.96 billion US $. The damages are bigger and bigger and cost more and more. This can be due to the number of people affected by these episodes, also the people live closer to the flood plains that are more likely to be flooded.

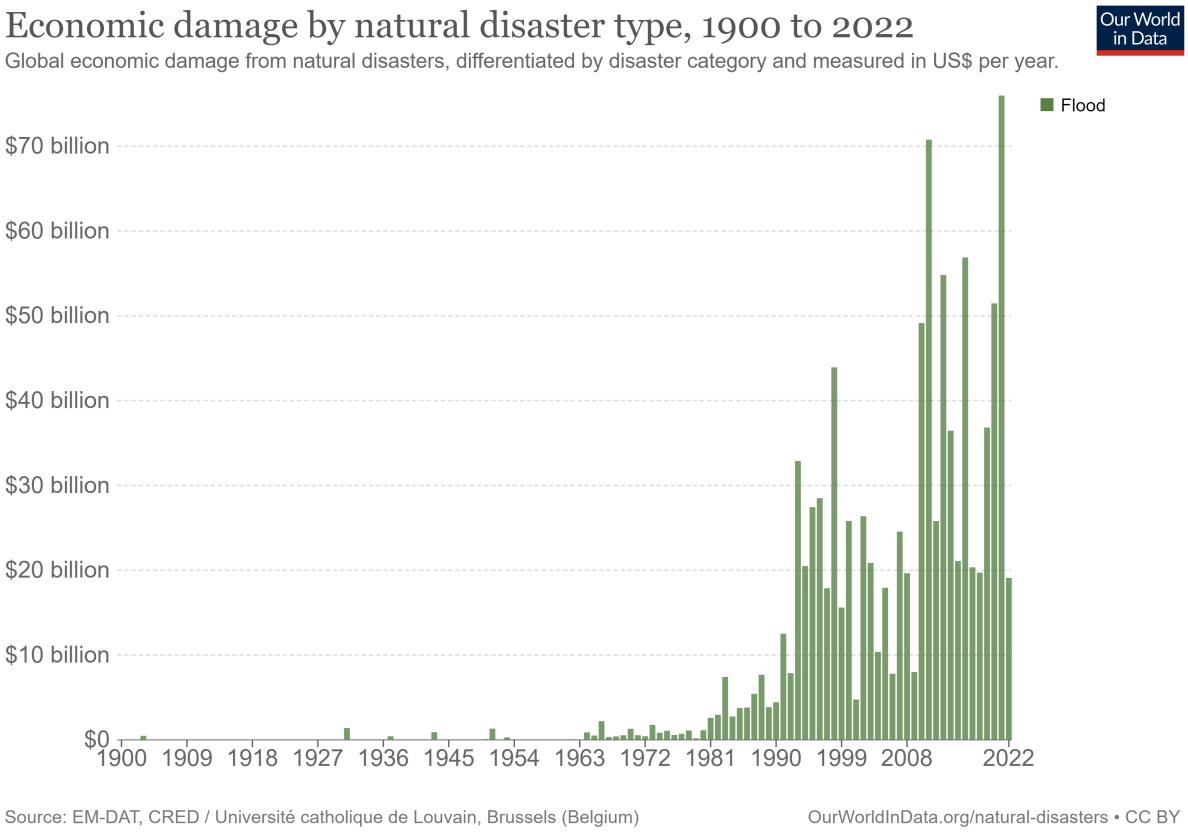


Figure 1.6: Economic damages by floods. [22]

Here, we can see the portion of the total people affected in the World. There are more people affected in south and east Asia and sub-Saharan Africa. This is explained by several large, densely populated areas that are in areas of high flood risk, such as coastal areas or flood plains. In Asia, monsoon rains fall very hard which brings a large amount in a small time and causes major floods.

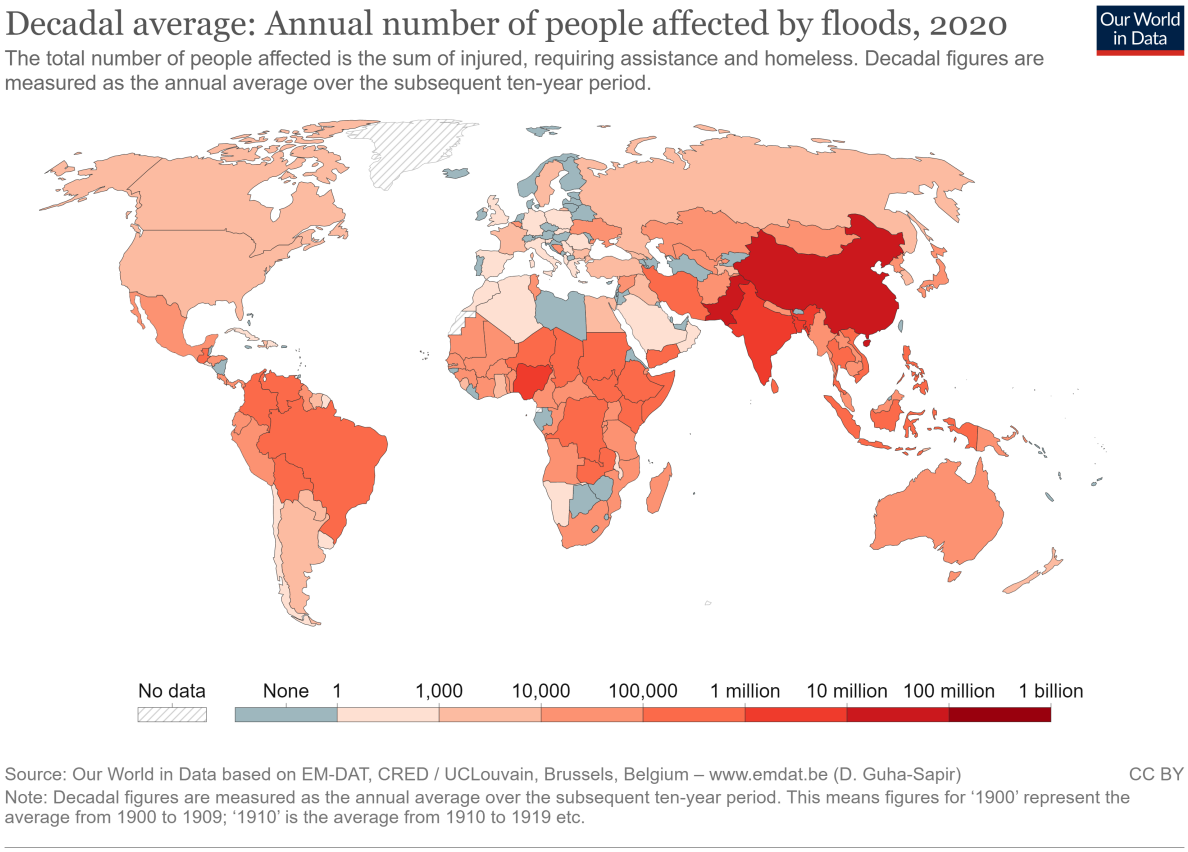


Figure 1.7: Decadal average of people affected by floods. [22]

This section is written from the information on the site "IRM-Observations historiques d'inondations jusqu'à la fin du 19ème siècle" [12]. In Belgium, there were already a lot of events of floods. Here, the term floods means the floods by overflow in the sewage system with high intensity rainfall or overflow of river due to long rainfall. Some floods occurred due to the melt of the snow. Indeed, when large rivers freeze during really cold winter, there can be some ice sheets that are formed and overlaid. These ice sheets can block the river and causes grave floods. At the end of the 19^{th} century, the data began to be collected in Belgium about the weather.

Here are some important floods occurred since 1900. The first one in January-February 1910 occurred in France but also in Belgium. In France, especially in Paris, a lot of districts were drowned due to the overflow of the Seine. In Belgium,

due to heavy precipitation and the melt of the snow in the Ardennes, the south of the country is flooded. Dinant and Namur are two cities that were highly affected. A few river reached their highest level since 30 years. The biggest flood in the 20^{th} century in Belgium happened in December 1925- January 1926. First, at the end of November and the beginning of December, there was a massive fall snow. Then a rain with high intensity fall. These two phenomena lead to an exceptional flood of the Meuse. For example, at Liège, the discharge reached 3500 m^3/s compared to the mean 205 m^3/s. All the cities of the valley of the Mosanes are underwater and the water reached the first floor of some houses. In January - February 1953, Belgium, the Netherlands and Great Britain were affected by devastating floods due to a violent storm and a big tide. At the coast, a few coastal cities are overflowed due to the violence of the water that broke dikes. Besides some deaths at Ostende, the break of the dikes affected some regions that were importantly flooded. In Belgium, only a few people died (14-22 people), but in the Netherlands the death toll is dramatic and reaches 1800 victims. In January 1976, the same scenario occurred but with no deaths. In December 1993, 1600 people had to be evacuated in emergency due to a very high total pluviometric in the country. One year after, in January 1995, a catastrophic flood happened again. A rain with high intensity falls since December, and the snow melt at the same time. Since November 2010 until January 2011, the country is under a meteorologic alert. Some stream overflows that never overflowed in the previous floods. More recently occurred a big flood in July 2021. Indeed, due to big flooding, more than two hundred people died in the month of July 2021. In Europe, especially in Belgium and Germany, big floods and landslides occurred due to big rains. All of this to say that floods are a big challenge to which we have to find solutions and mitigation.

On the other hand, the water stress and the risk of water scarcity is a big concern nowadays. The global population constantly increases and the water demand also increases but the water resources lower. The water stress is defined with the ratio of freshwater withdrawals to renewable fresh water resources. The water stress gives an indication of how it is probable to exceed the water renewable resource. Exceeding the water withdrawals may be the consequence of two situations: the extraction of water with a higher rate than the rate of to which the aquifer replenishes or a high capacity of desalination water generation. There are different categories of water stress in percentage of withdrawals with respect to the renewable resources. Below 10 %, the stress is low, between 40 to 80 % the stress is high and over 80 % the stress is extremely high. When the water demand exceeds internal water resources, we have water scarcity that is more extreme than water stress.

Here we can see the distribution of the internal renewable freshwater resources, that is the internal renewable resources. It is an important factor because if the water demand exceeds the renewable water resources it means that the resources will decrease and not be enough replenished.

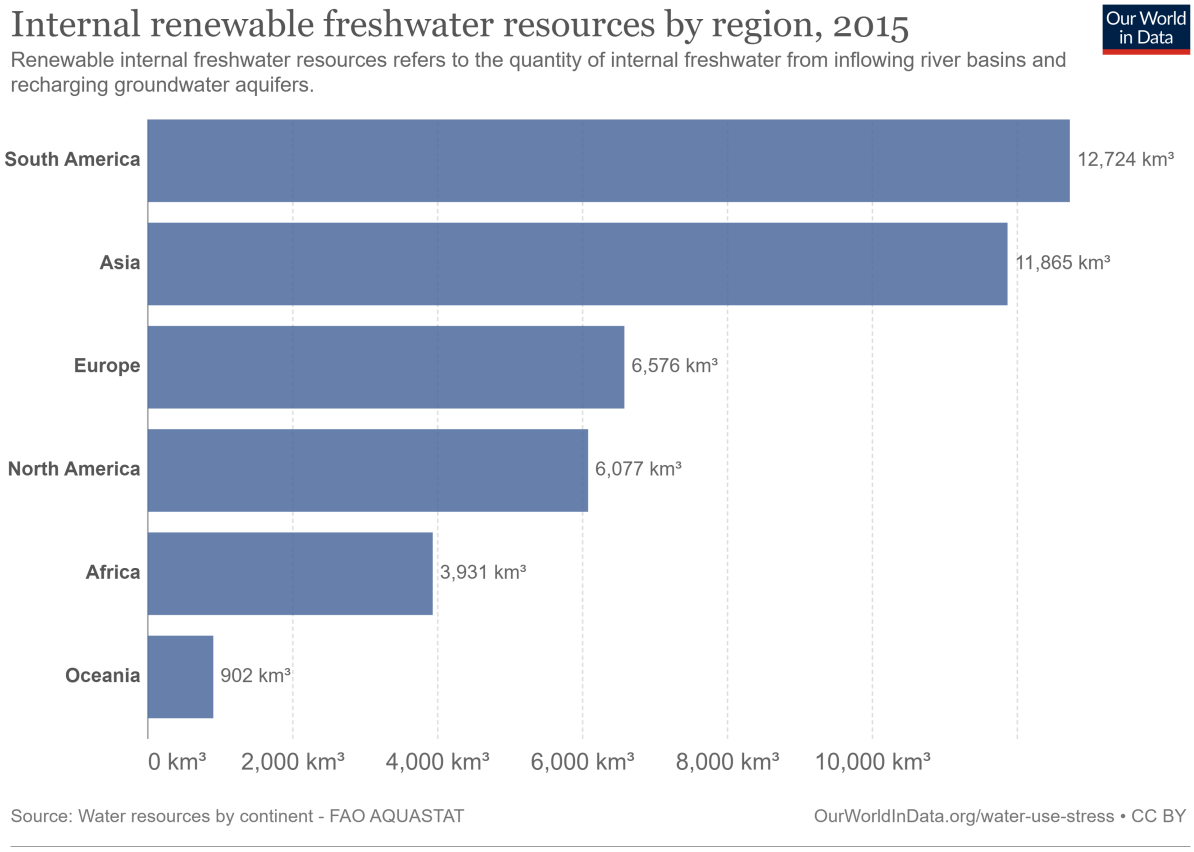


Figure 1.8: Renewable freshwater in 2015.[23]

In the next two graphs, we can see the renewable water resources per capita. The per capita resource depends of the total quantity of the renewable flows and the size of the population. It means the renewable water resources available by people. So, if the population increases, and the total resources stay constant, the per capita will decrease. In the same way, if the total resources available decrease, the per capita will also decrease. We can see that in the World, as in Belgium, the renewable water resources per capita declines.

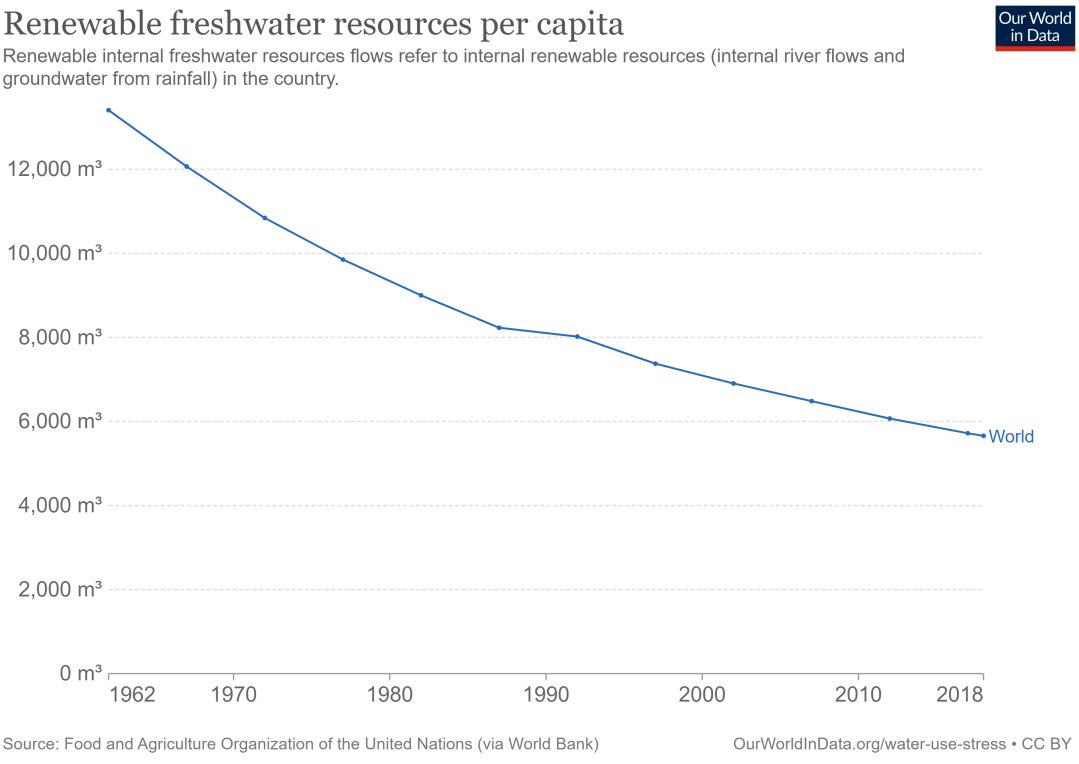


Figure 1.9: Renewable fresh water resources in the World. [23]

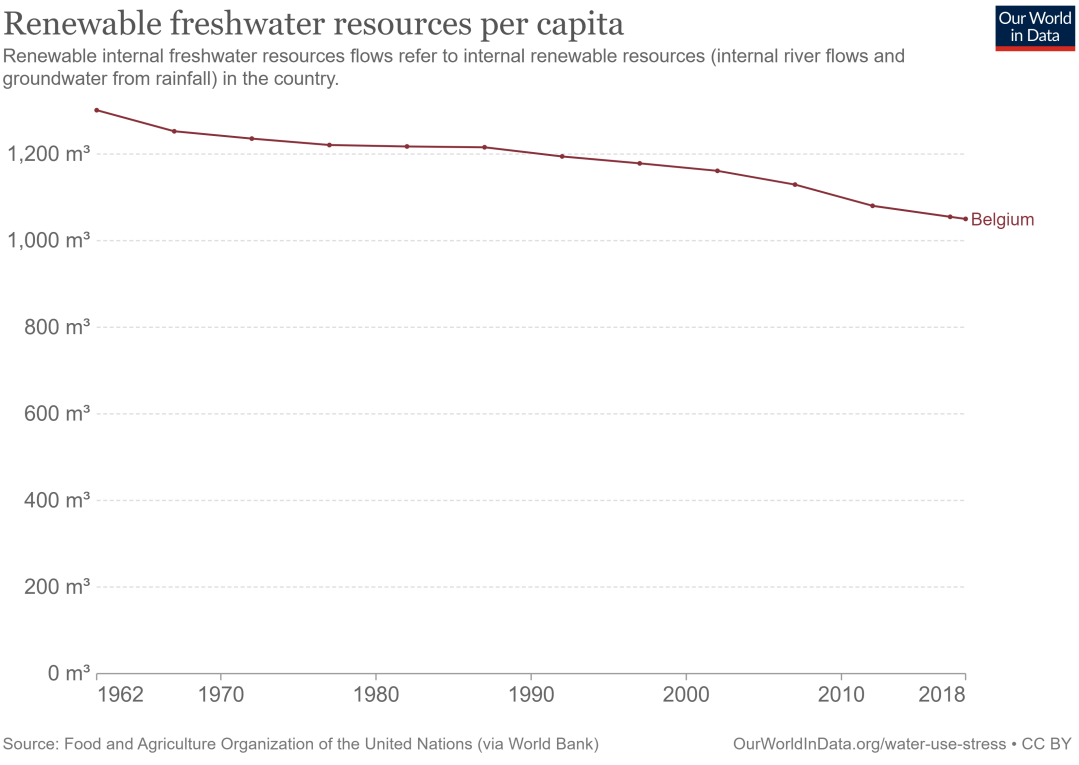


Figure 1.10: Renewable fresh water resources in Belgium.[23]

Now, we can compare this resource with the use of freshwater. We can see on this chart the use of freshwater for agriculture, industry and municipal use. This use of freshwater increased a lot in the World. But if we compare it to the freshwater withdrawal of Belgium, we can see that the consummation of Belgium decreases. The water withdrawal is the freshwater taken from ground or surface and used for agriculture, industry or domestic use.

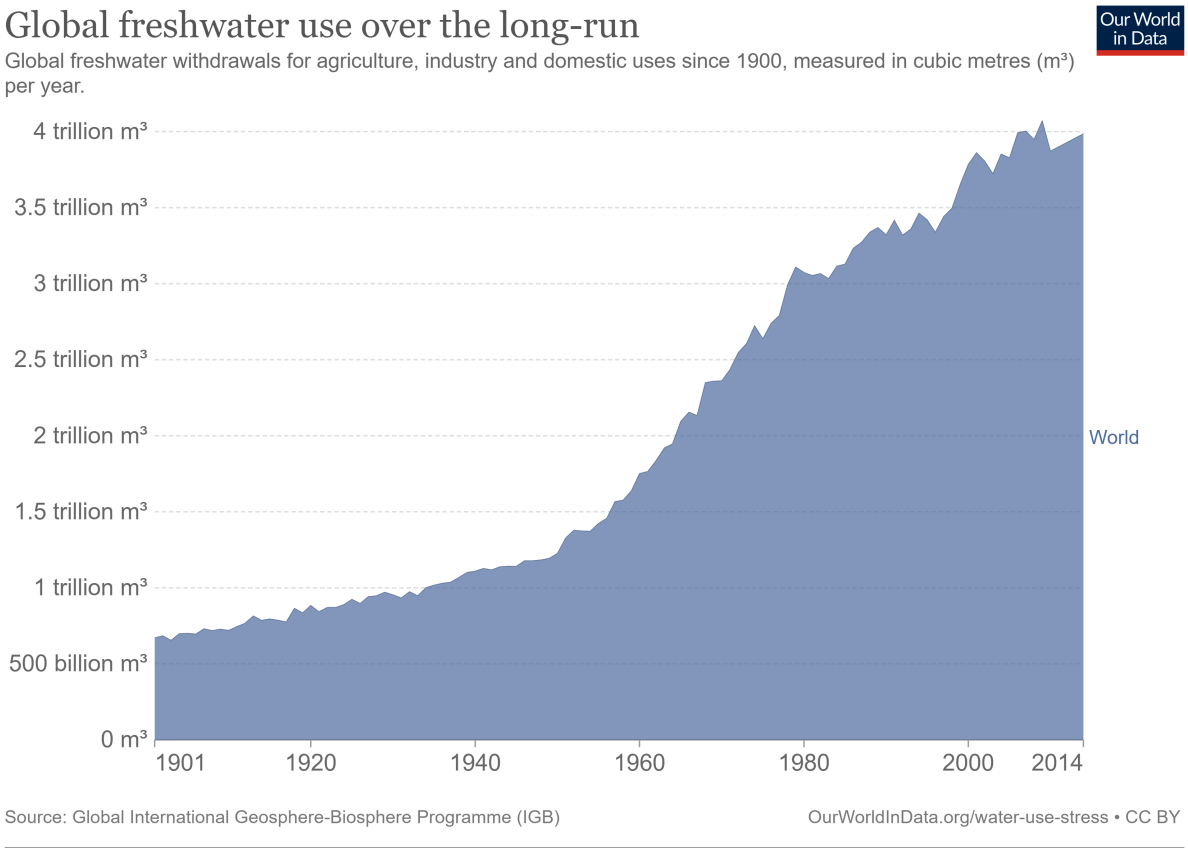


Figure 1.11: Global freshwater use in the World.[23]

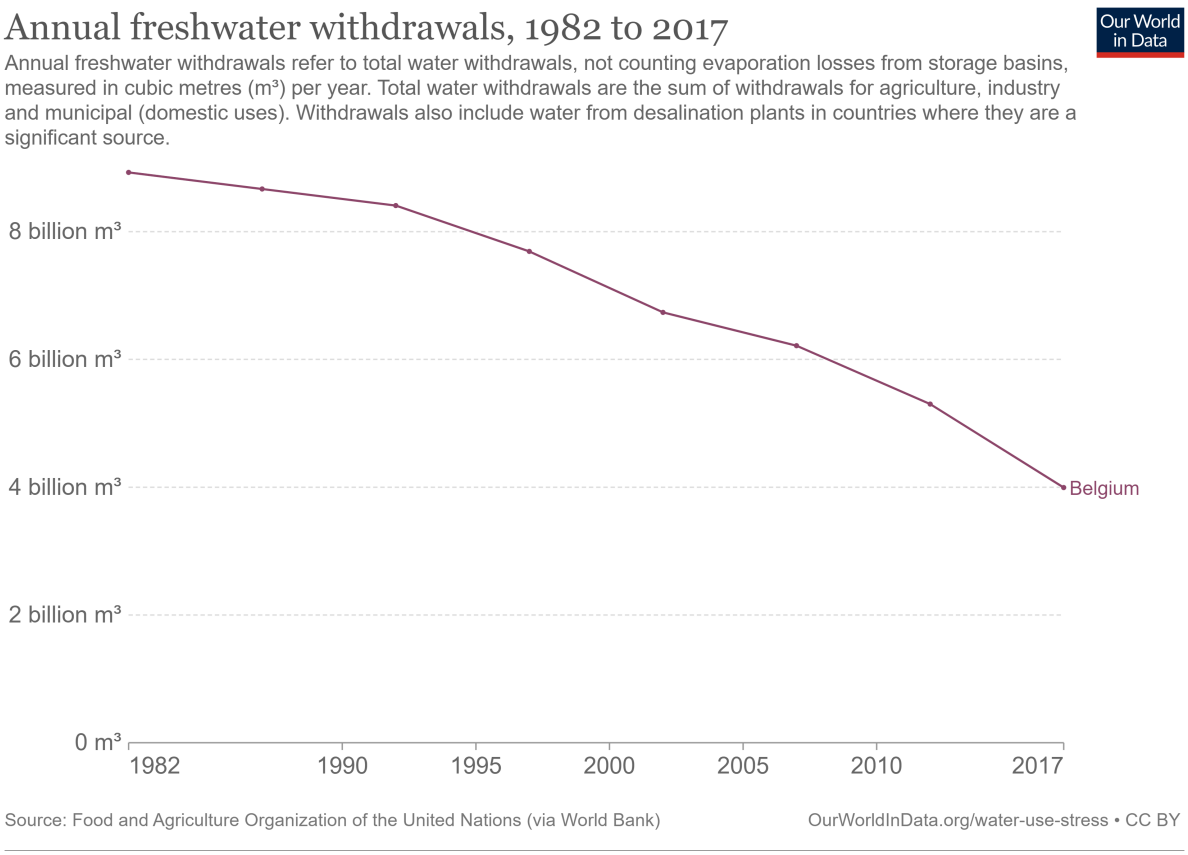


Figure 1.12: Annual freshwater withdrawals in Belgium. [23]

Now having all this data, we can talk about water stress. Here the scale to know the magnitude of the stress is based in the withdrawal compared to the resources of the country : withdrawal less than 25 % of the resources means no water stress, between 25 and 50 % low stress, between 50 and 75 % medium stress, between 75 and 100 % high stress and greater than 100 % critical stress. In this map, we can see that critical stress is mainly present in the Middle East and in the North of Africa, that means that they extract water from aquifer in a unsustainable way or produce a large share of water from desalination. If we focus on Europe, the North of Europe isn't reached by water stress but the middle of Europe and Spain has a low water stress. One country is in medium stress and it is Belgium. If we take the history stress of Belgium, in 2000, the percentage of freshwater withdrawal with respect to the resource was 92 %, a high water stress, now we are at 54 % and this share seems to stabilize.

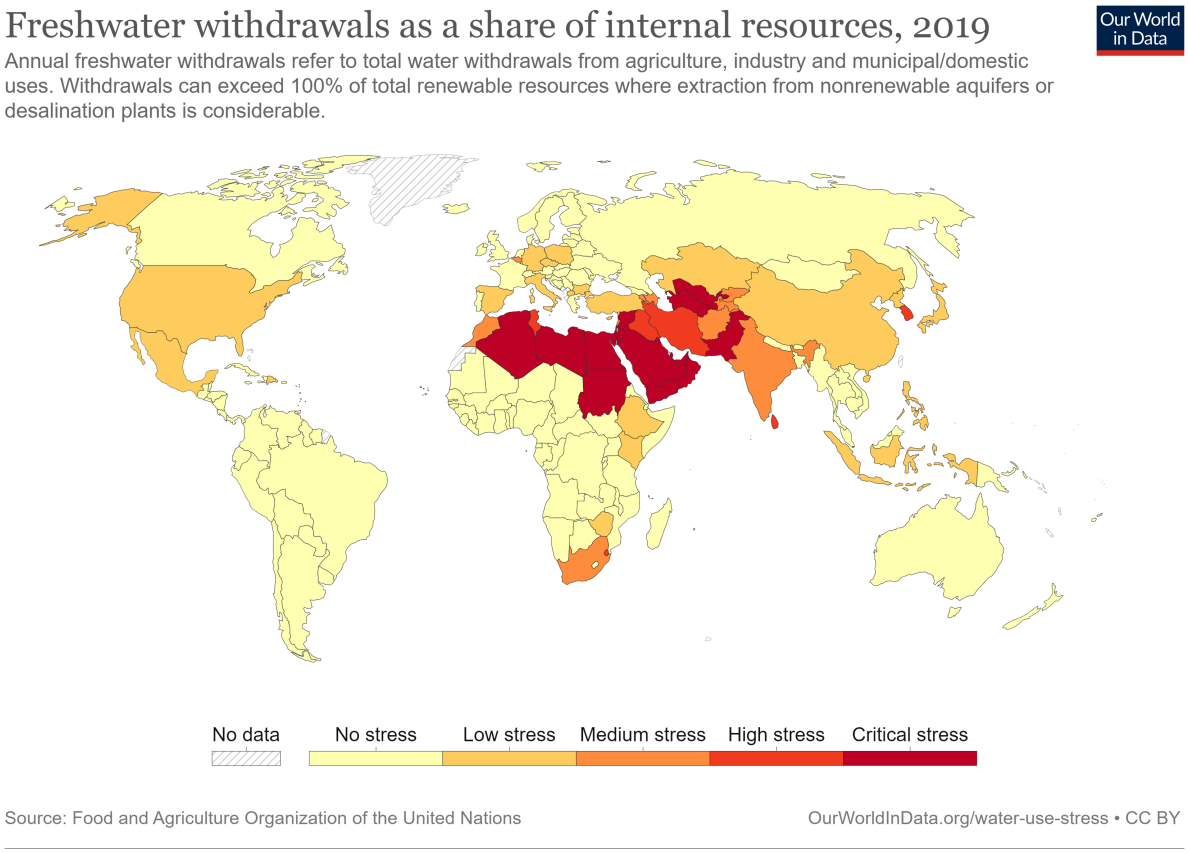
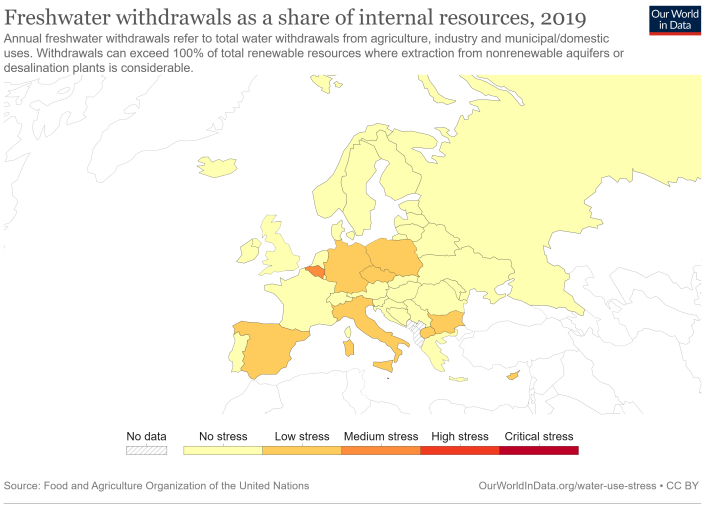
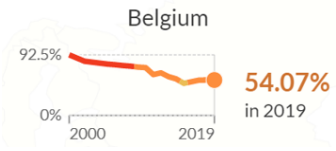


Figure 1.13: Freshwater withdrawals in the World. [23]



(a) Freshwater withdrawals in Europe.



(b) Freshwater withdrawals in Belgium.

Figure 1.14: Freshwater withdrawals in Europe. [23]

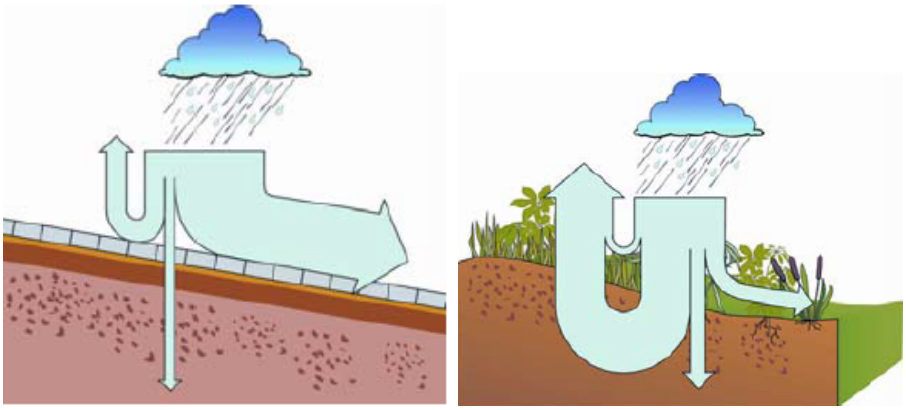
1.2 Mitigation of floods in urban and non urban area

The use of water in the World and in Belgium is a big concern, this is why some simulations of rain and their impact on area were already done. Also, in Belgium the infiltration of the water is a subject that is already in the center of attention. Here I will explain some mitigation measures that are already studied.

In Belgium, despite the high number of rain that the country receives, the Flanders part is in medium water stress. The biggest causes of the water stress are human factors such as the increasing population, the intensive farming, deforestation, pollution and even the global warming due to rejection of CO_2. This water stress has impacts on the growth of the vegetation, and leads to a difficulty to grow fields of agriculture. The pollution has an impact on the quality of the water, and the fact that aquifers have a level of water decreasing, the resources decrease also and can lead to a degradation of the water. Moreover, saline water can intrude fresh water river. The main solution for places located at the boarder of sea or oceans is the desalination of the saline water. It allows to produce fresh water without extracting water from aquifers. Another lever is the treatment of used water, this water can be used for domestic use, agriculture or even industrial use.

If we focus more on urban area, one major problem is the runoff. One of the main factor is the population living in the cities. If we take some numbers, in 1950, only 30 % of the population lived in cities, in 2022, 55 % of the worldwide population live in cities and we expect 68 % in 2050. The cities become more and more vulnerable to climatological phenomena such as floods and heat waves. The cities are well known for the imperviousness of their soil. It can come from some human developments such as roads but also from agricultural practices on the ground leading to settlement, that produces a lot of runoff and it also increases the speed of the water flow. These two factors can induce more floods. The dominant deal in the cities is to decrease this runoff that doesn't have a flow path really predictable due to the heterogeneity of urban soil's type. It is based on a balance between what falls on the ground by precipitation, which part can be evacuated by the irrigation network, and water that can be stored temporarily. One of the solutions is the temporary storage during rainfall event with for example retention basin and also the natural storage in the soil through the vegetation. Indeed, it helps the infiltration in the soil and can also be beneficial against heat wave.

Another solution, is to lower the imperviousness of the soil in order to reestablish the natural cycle of the water, conserve the essential functions of the soil and it will mitigate the effects of the climate change with the vegetation that will have the role of freshness island. We have to be careful when looking at the infiltration, we have to add the dimension of the depth. Indeed, the pervious area can be saturated at a time, so the solutions will not really be useful when this saturation is reached. Some solutions based on vegetation can be the swales that are open ditches collecting or infiltrating the rainwater; filtering and draining trenches that are linear trenches filled with porous media that temporarily stores rainwater, and runoff, it releases the flow with a delay; porous media that helps the infiltration in the soil; green roof with a vegetation cover; rain garden that retains water collected in a surface varying to the surface of individual house to a big urbanism era. All these green solutions have also other impact than only on the runoff. For example, a greener city can lead to a better public health because the trees depollute the water and the air, so people are less likely affected by respiratory pathology. It also destresses the people, and the last point is that it will help to a better fauna and flora.



(a) Precipitation on urban soil. (b) Precipitation on natural soil.

Figure 1.15: Precipitation on urban and non urban soil. [11]

Except the green solutions, we have also structure reservoirs that collect rainwater, store it temporarily and then release it. These structure reservoirs are designed for big events of rain.

After the design of mitigation solutions of runoff, we have to be careful at some other designs such as the design of the roads where the perviousness of the coating is not necessarily voluntary. When the roads are not well maintained, there may be seepage through cracks or between the joints of the coatings. For example, when

there is a bowl, there is an accumulation of the water and it tends to infiltrate. If the streets are parallel to the slope, the water will speed up and will tend to less infiltrate but if the streets are parallel to the level curve, the water will speed down and tends to infiltrate less. It shows that a lot of aspects has to be thought in the design of the city in term of runoff.

Another concerning problem of the cities is the combined sewage system. The water coming from wastewater and rain goes to the same sewage system. Actually, 80 % of the rainwater goes to the sewage system and only 20 % will be soaked in the soil. But the problem is that the sewage system is not designed for big rain event. So, when there is rain with a high intensity or a long lasting, the sewage system has a too low capacity and it leads to overflow. Moreover, it can also reject pollutants to the nature due to the overflow.

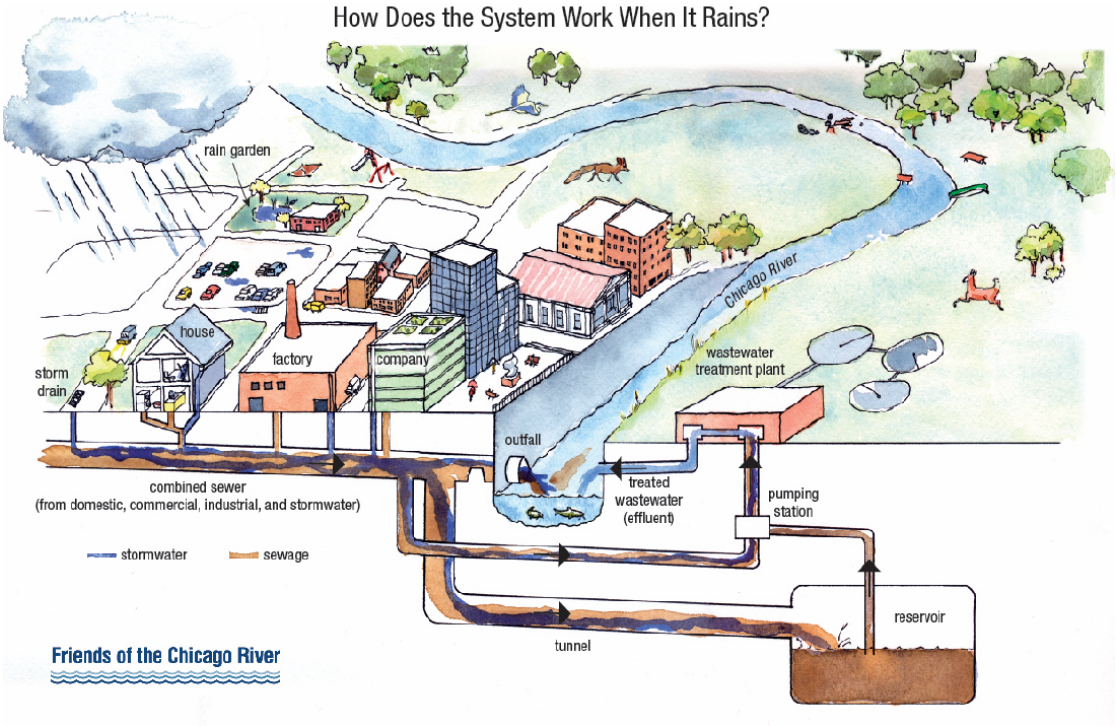


Figure 1.16: Hydrological cycle in urban area.[14]

Now that we know that cities are really vulnerable to floods due to runoff and big precipitations, a key factor is to determine the vulnerability and their resilience to floods. According to Barroca and al. [8], the vulnerability is here defined as the susceptibility to have damages in respect to some different factors. The risk of floods can be defined as the vulnerability times the exposure of the city. The vulnerability depends on the context and the type of events at which we look. To

define the vulnerability we have to go through different steps. The first one is to asses the complexity of the vulnerability, because the hazard can take various forms and can be very complex. Then, we have to determine which elements are at risk and then can be affected by the risk. Finally, we have to think about the relations between these objects at risk. Here is an example of a vulnerability assessment tool :

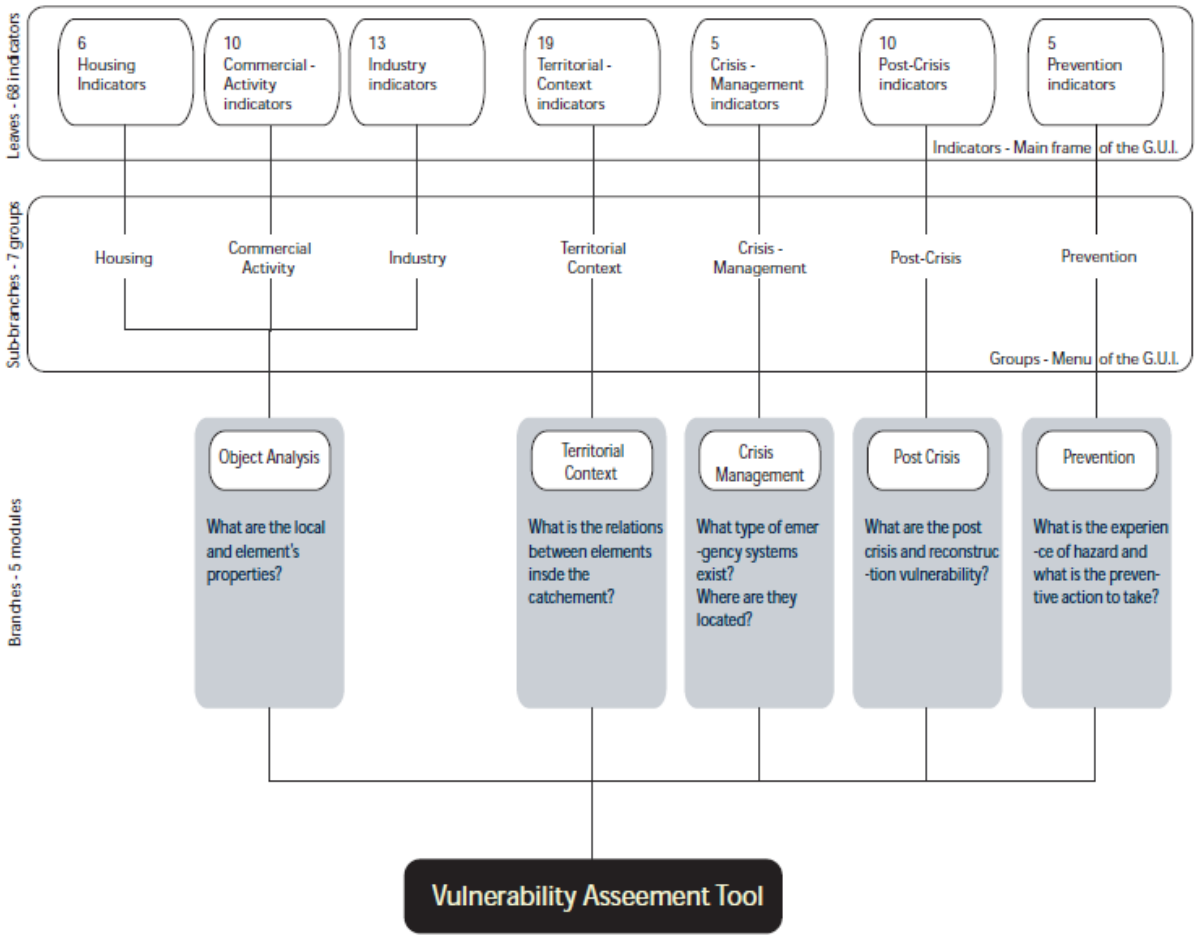


Figure 1.17: Vulnerability assessment tool. [8]

At the opposite of the vulnerability, the resilience, according to Barreiro and al. [7] is the global capacity of the city to survive, adapt and prosper in stress and chaotic situations. Due to the climate change inducing the rise of the sea level, some irregularities in term of the frequency and intensity of the rain, drought and heat wave, it is really important to assess this resilience. We can see the city as a system of systems that have to resist to some external phenomena. The methodology to assess the resilience is based on four steps. The first step is the data collection that permits to define and characterize the subcatchement studied. In particularly we define the zone of the watershed, the infrastructures and the criti-

cal services. Then we look at the normal and extraordinary conditions, and we also look for human and physical resources that can be used in case of emergency. The second step is the data treatment and the analysis. Based on the data collected, we can identify the interdependence and the redundancy between all the services and the infrastructures. It is also important to see further with the political administration and the different services that could be overlapping. The third step is the modeling of the impact of extreme flood with different return period. This modeling will depend on which software is used. The last step is to evaluate the urban resilience by calculating five resilience indicators : the volume overflowed, the flooded area, the flood duration, the buildings affected, the services affected. These five indicators are the proportions between the undesirable effects and the total of input. The assessment of the resilience is useful to model future scenario to see what kind of solutions we can set up before the catastrophe happened.

In order to assess some flood mitigations, the choice of the watershed was leaded by different factors. Firstly, the watershed observed is in the Walloon part of Belgium for the ease of obtaining and understanding data. Moreover, the data in Belgium, between Flanders and Wallonia have some disparities. For example, the elevation of the sewage system is different at the boundary between the two regions. A second parameter was to find a watershed with some floods episodes for which the cause of these floods was clear. The choices were really vast, but it had to be an urban area. The watershed of the Petite Espierres is the final choice. It is a good choice for the modeling because the floods were really localized and the zone is well divided with a pattern of houses. Moreover, there are different types of floods that occurred. This study can be beneficial in a lot of locations because the mitigations studied can be applied to other places.

Chapter 2: State of art

2.1 Hydrological cycle

The hydrological cycle is the entire process of transformation and transfer of the water under the three states (solid, liquid, gas) between the water reservoirs on Earth (oceans, atmosphere, lakes, streams, groundwater and glaciers). This cycle is possible thanks to the solar energy that permits the evaporation of the water and entertains all the other exchanges.

These water reservoirs have different characteristics, the storage volume and the residence time that is the average time a molecule of water stays there before moving to another reservoir. The different reservoirs on Earth are the salt water in the oceans with 1370 10^6 km^3, that represents 97.25 % of the total volume of water reservoirs, his residence time is 3200 years. Then the glaciers and ice caps whose water is stored for a time in the form of snow or ice. Their melting is more or less important according to climate variations. The volume is 29 10^6 km^3, that represents 2.05 % of the volume of water reservoirs and their residence lifetime depends if it is coming from Antarctic or glaciers that is respectively 20000 years and from 20 to 100 years. All the others reservoirs represent less than 1 % of the total volume of reservoir water. In these other reservoirs, in decreasing order of volume, there is groundwater contained in aquifers with a residence time varies from 100 to 200 years in shallow aquifers and can go through 10000 years in deep aquifers. Also, surface liquid freshwater with streams, lakes, freshwater ponds, marshes with a residence time from 50 to 100 years; water in the soil with a residence time of 1-2 months; atmospheric water with water vapor and clouds with a residence time of 9 days, and finally the water contained in living beings. There is a last reservoir that is the seasonal snow cover that stays 2 to 6 months.

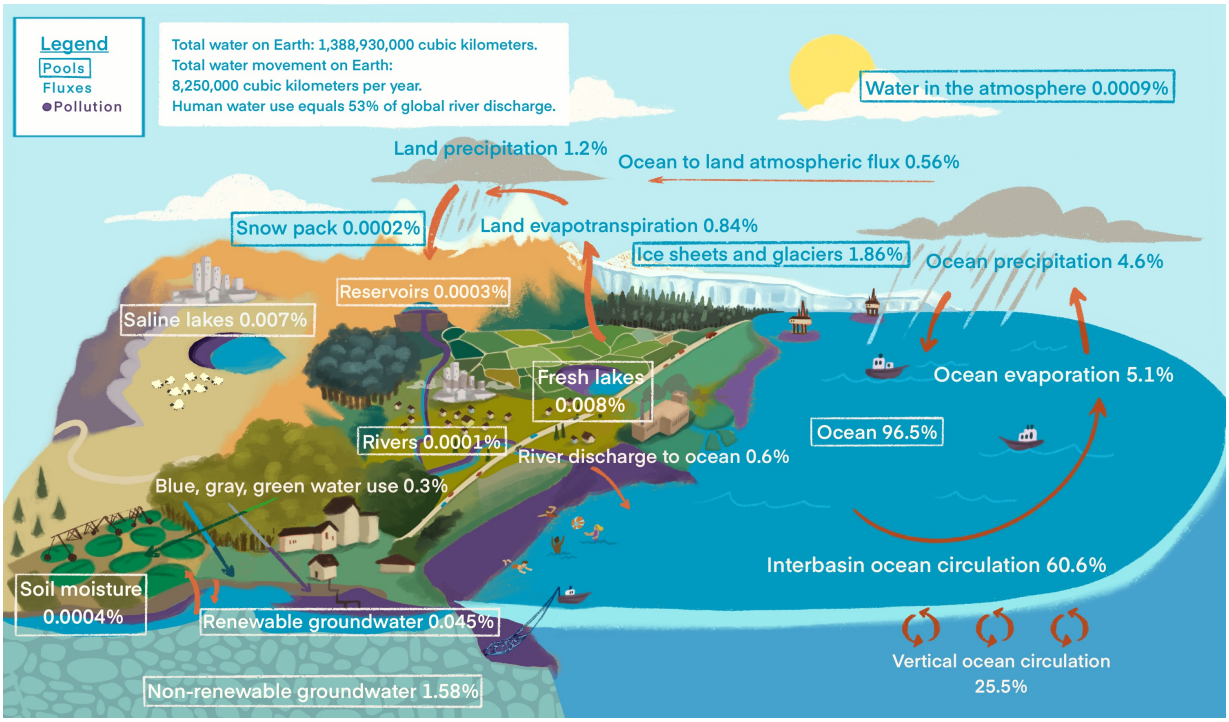


Figure 2.1: Reservoirs of water. [10]

Now, I will explain more in detail the flow between all the reservoirs. There are some main principles that permit the exchanges of the water between these reservoirs. These exchanges are governed by the evapotranspiration, the precipitation, the runoff, the groundwater recharge and the groundwater flow.

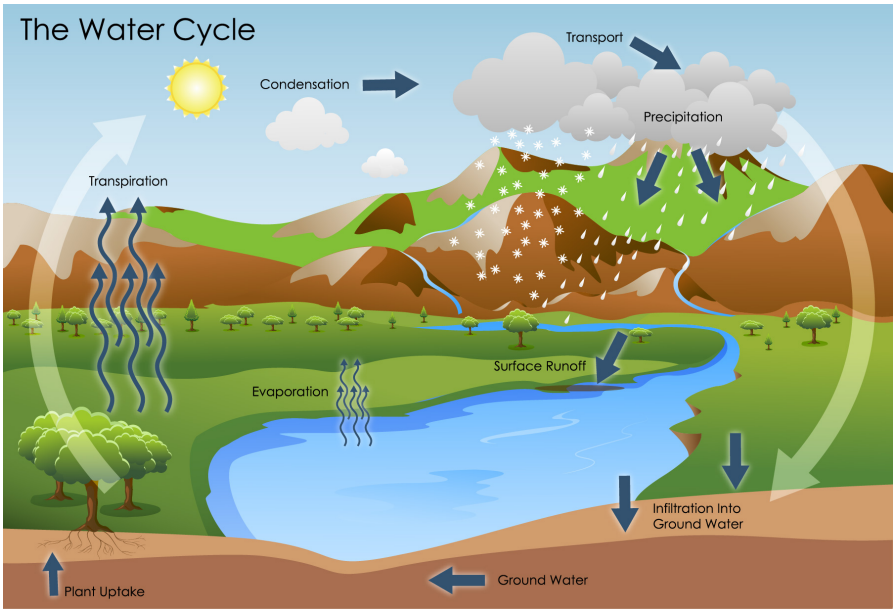


Figure 2.2: Water cycle.[29]

The evapotranspiration is the biophysical process of transferring a quantity of

water to the atmosphere, through evaporation at ground level and through transpiration from the plants. The evaporation of the water is the progressive change of the water between the liquid phase and the gas phase. The evaporation of the water is due to the warming of the waters thanks to solar radiation. Then, the water reaches the atmosphere under the form of water vapor. The evaporation depends on some parameters such as the amount of water available, the degree of steam saturation of the air, wind, sunshine, temperature,... When the atmosphere is not saturated in water, a part of the precipitation can be directly evaporated. This evaporation continues until the atmosphere is saturated. The more we are near to the surface of the soil, the more the evaporation is efficient. The transpiration comes from the plants. This is the continuous process caused by the evaporation of the water by the leafs and the water pumped in the soil with their roots. The evapotranspiration is influenced by a lot of parameters such as the type of plants, their growth, height and the depth of their roots. There are also geological parameters such as the rate of the soil covered by the plants, the solar radiation, the humidity and the temperature of the soil, the composition and the capacity of retention of the soil.

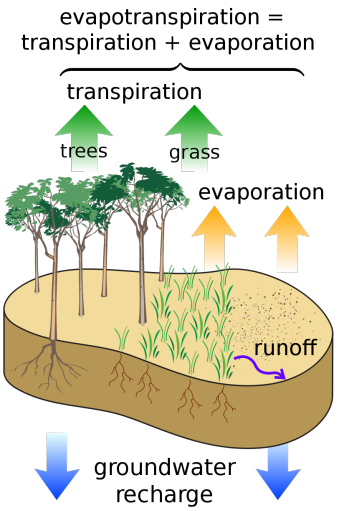


Figure 2.3: Evapotranspiration.[3]

The precipitation is defined as all the forms of water at the liquid or solid state coming from the atmosphere. After undergoing condensation and aggregation processes within the clouds, these hydro meteors (ice crystals or water droplets) reach a point where they become too heavy to stay suspended in the atmosphere. They either fall to the ground as precipitation under the form of rain, snow, hail, dew, or evaporate into virga before reaching the soil. The entire water evaporated falls into precipitation, and the main part falls into the ocean (7/9) and the other part into the continents. Precipitation can be described based on three parameters:

volume, intensity, and frequency,. These parameters vary depending on the specific location and time frame, be it days, months, or years. There are different mechanisms of formation of the precipitation : the condensation that is the process in which the droplet begins to form when the air is slightly over-saturated under the freezing point, the water vapor settles on some impurities and forms a drop; the coalescence that is the amalgamation of two or more droplets by collision to form a larger droplet; the Effet Bergeron is when the ice crystals formed by droplet freezing, have a saturation pressure lower than the surrounded droplets, the droplet evaporates and the water vapor settles on the ice crystals that will fall and form snow by coalescence.

The runoff is the water flow at the surface of the earth. The runoff depends on the precipitations. Also, the runoff depends on the infiltration capacity of the soil, and the capacity of retention of the water in the soil. The imperviousness of the soil is also an important factor about the intensity of the runoff. The runoff can lead to the erosion of the soil.

The restore of the aquifers, also called infiltration, is the hydrological process in which the surface water percolates through the soil or infiltrate through natural cracks of the soil or rocks and accumulates into an impervious subsoil. The aquifers are naturally filled with precipitation and the snow melt, but also with the surface water flow. As the aquifers are used to pump the water for the agriculture or for drinking water, it is important to restore these reservoirs. In the aquifers, we should do the distinction between a shallow aquifer at the surface and deep aquifers that can be at hundred meters under the soil. In general, we pump the water from the shallow aquifers. But when we don't have enough we go to deeper aquifer that take a lot of time to restore.

The groundwater flow in the aquifers is slow, at the order of 1 cm/year. This speed depends on the type of soil the water goes through. The water of these aquifers joins rivers by sources or ocean and atmosphere.

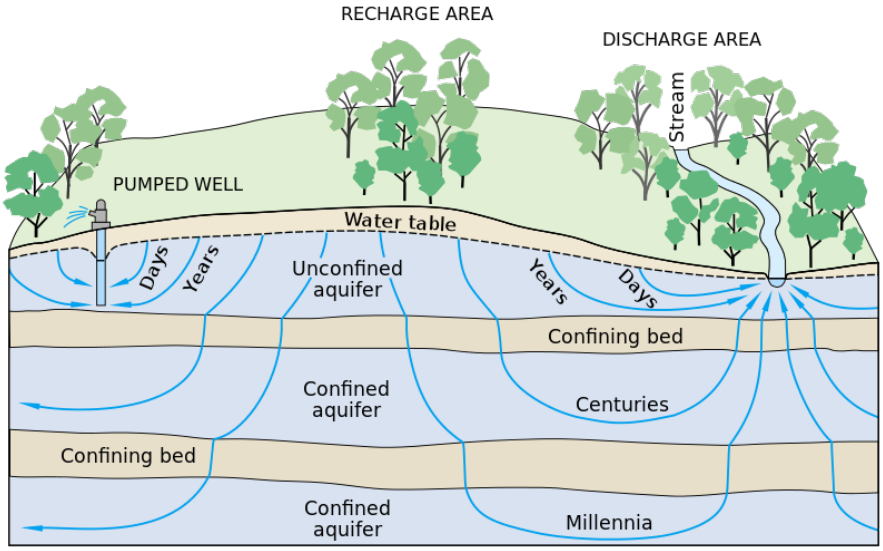


Figure 2.4: Aquifers.[4]

This water cycle can be disturbed due to the presence of the human civilization. The urban area generates problems in the hydrological cycle. Indeed, in order to construct city or prepare agricultural fields, a lot of natural areas had to be deforested. This deforestation leads to increasing runoff because the roots of the trees retained water in the soils and the soils don't absorb water anymore. The evapotranspiration is not insured anymore. The other problem is the imperviousness of the soil, in a city main part of the parcels are totally or partially impervious. It tends to less infiltration and so more runoff. The water that produces runoff has to go somewhere. So, this flow will join another flow that wasn't initially meant to be joined by another stream. It can lead to local floods but also to floods in the downstream part of the city. This imperviousness avoids the storage of the water in the aquifers that can lead to a water stress in some countries. The water will go through some materials that contains contaminants, this water will reach other natural water and will transport these contaminants. Therefore it is important to study the urban area in the hydrological cycle in order to prevent floods and increase the infiltration of the water to store more water in aquifers.

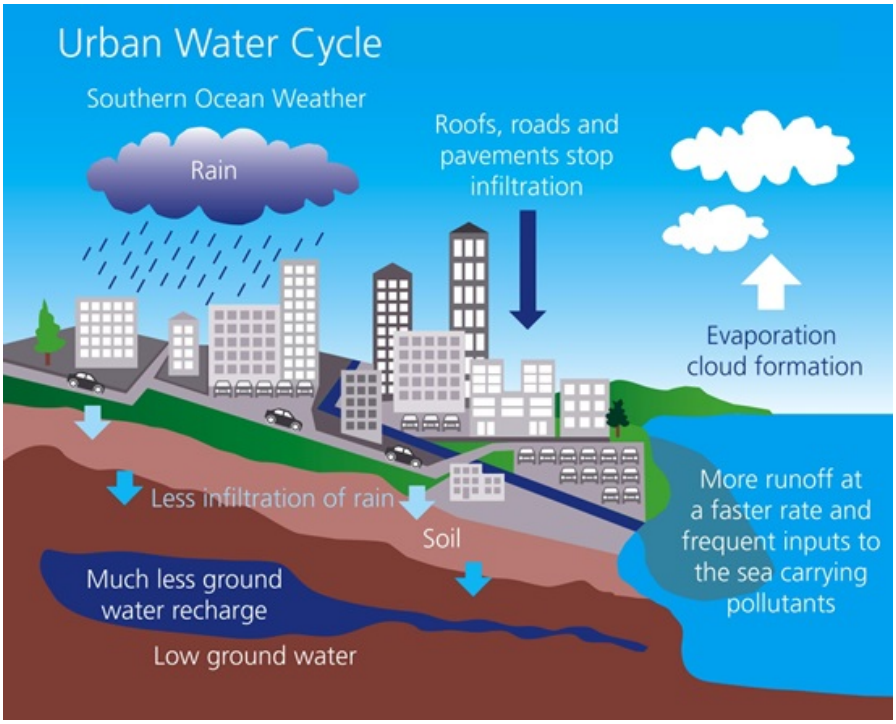


Figure 2.5: Urban water cycle.[1]

2.2 Hydrological modeling of urban areas

An hydrological model is a description of the mechanisms that goes into a watershed. The watershed of a point is the surface where when a drop of water falls in, the water will flow to that point. For example, the watershed of a river is the surface where, when there is rain, due to topography, the water will flow down to the river.

Nowadays, it is impossible to describe precisely all the elementary mechanisms occurring in the watershed. We only have simplified solutions.

An hydrological model also known as a rain-discharge model is a numerical tool allowing to represent the relation between the rain and the discharge at the scale of a watershed. Since the end of the 1960, a lot of hydrological models were developed. Here are some possible representations of an hydrological model.

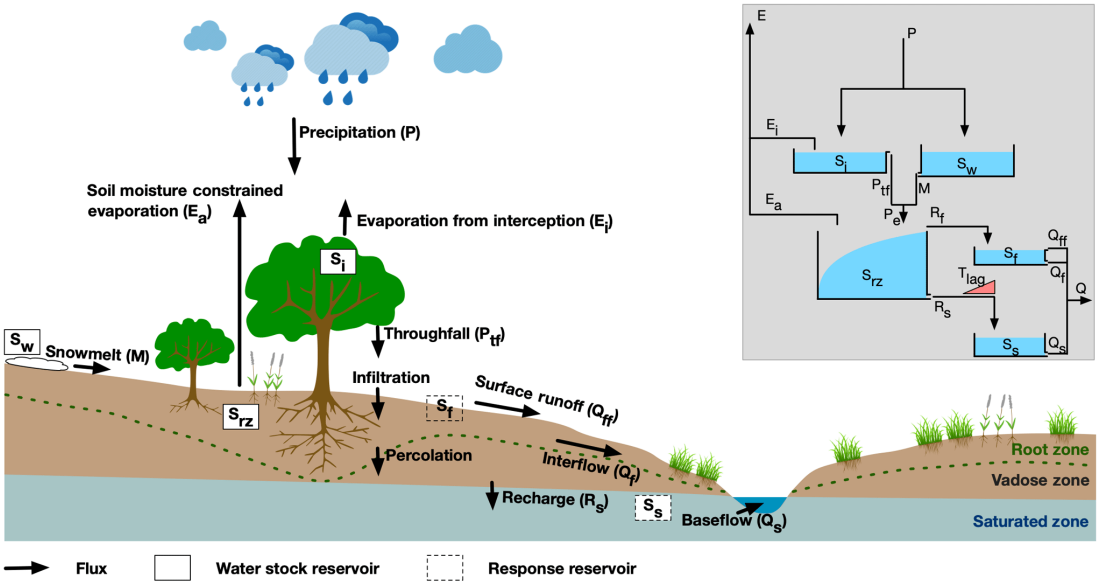


Figure 2.6: Hydrological model.[15]

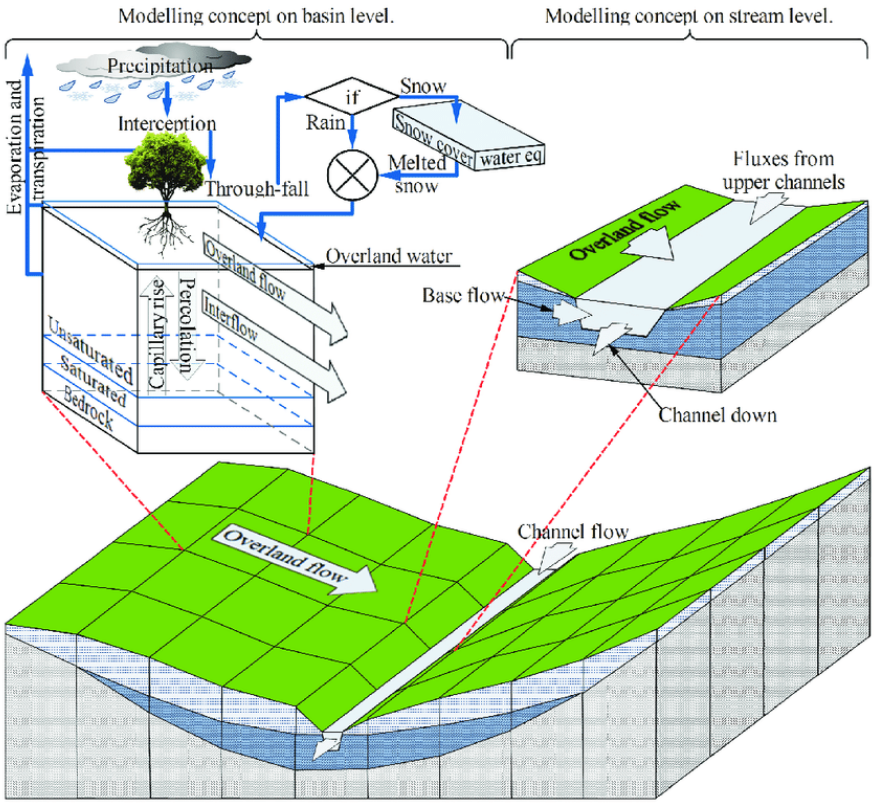


Figure 2.7: Hydrological model. [13]

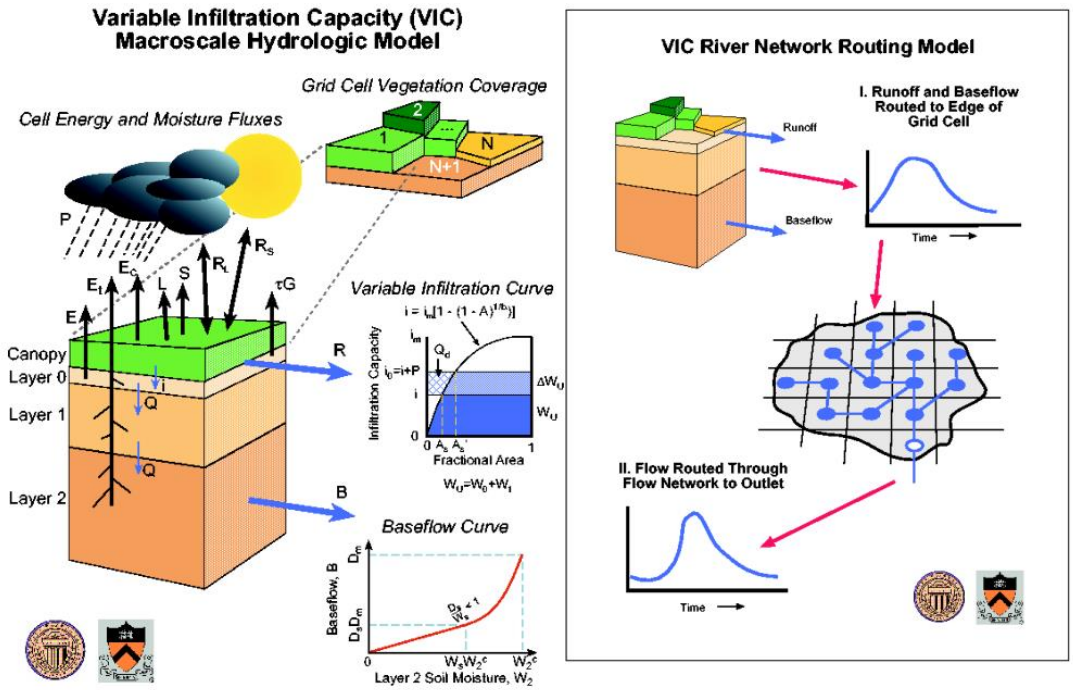


Figure 2.8: Hydrological model.[18]

Hydrological models can be used to forecast floods, low water level, to predetermine extreme discharge, to do some hydrological or climatic studies,..

How to transform the intensity of the rain into a discharge? The process is divided into two parts. The production that permits to categorize the quantity of total rain into different categories - net rain, water involved into evapotranspiration, water stored by the watershed -. The transfer that distributes the quantity of water involved to the discharge of the watershed.

It exists a lot of hydrological models and different classifications of these models depending on which characteristics are put forward.

One of the classification consists to look at the different representations of the process :

- Empirical model : All the mathematical relationship are obtained by looking to the input and output to the watershed. It doesn't describe the process. So, it's often called a black box model.
- Conceptual model : It represents the main process about the relation rain-

discharge without using physic laws. It is often constituted by connected reservoirs that represent different sections of the watershed. So, it is the model that is the most likely to be used in urban area.

- Physical model : It represents the process about the relation rain-discharge using physic laws.

The other classification is based on the representation of the space :

- Global model : The watershed is represented as a single homogeneous spatial entity. The spatial variability of the process is not taken into account.
- Semi-distributed model : The space is discretized along hydrological or topographic criteria for some modelling process.
- Distributed model : The space is discretized into spatial entities along a regular mesh or sub-watershed. As in urban area, there are different land use, it is the best model to use.
- Temporal discretization : The discretization can be done by minutes, hour,day, month, year,..

An hydrological model is defined, in general, by different parameters which are the entries of the system described by the hydrograph- explained more in detail later- put in the model, the exit of the model that can be discharge at the outfall, or piezometric level. Some variables of the system describe the state of the system with respect to time. It is also important to specify the parameters of the law that are used for the modelling, such as the routing, or the model of infiltration - seen more in detail later-.

I will explain briefly some models that are commonly used for modelization of rain-discharge :

- GR4J : Is a model rain-discharge that needs only four parameters : the capacity of the routing reservoir, the capacity of the production reservoir, the parameters defining the different exchanges of water and the base time of the hydrograph. This model is used for the simulation of low water, the environmental change or even the forecast of floods.
- TOPMODEL : Is a semi-distributed model. The parameters spatially distributed are the slope and the upstream surface drained, but the global parameters are the hydraulics properties of the soil and the precipitation. This model uses 8 parameters : the capacity of the routing reservoir, the

parameters of draining, the capacity of the interception reservoir, the delay, two parameters of topography index, two parameters of evaporation. It can simulate slow and fast answer of a watershed.

- HBV : Is a conceptual semi-distributed model. It has four routines : the snow routine, the soil moisture routine, the response function and the routing routine. This model needs only a few parameters. It is used to analyze river discharge and water pollution.

- CEQUEAU : Is a conceptual semi-distributed hydrological model that uses remote sensors and geographical information system. It is used to simulate and forecast the water flow and also the water temperature.

- Athys : Is a distributed model that is consists of 4 modules : MERCEDES a spatialized modelling platform, VISHYR a treatment of stationary hydro-climatic data, VICAIR a processing of spatial geographic data and SPATIAL a spatial interpolation platform. It is used for water resource management, prediction of extreme events, impact studies related to climatic changes.

- SWMM : Is a semi-distributed or global model, according to the discretization done, that can provide the volume and the quality of runoff in urban areas. A lot of parameters can be introduced in this model. It is the model used for this study.

In urban areas, as the land use is not homogeneous and there is the connection with the sewage system, the model needs to have a precise temporal and spatial distribution. The hydrological models focus, in general in one of the two main points. These two important are the hydrological processes and the hydraulics. They focus respectively on the evaluation of the impact of the urbanization or the possible sanitation solutions and the flow in the sewage system. But these two key points need to be introduced in one model in order to be able to respond to the environmental impact and quality of the water. There is a clear relation between these two problems. Indeed, alternative sanitation techniques recommends for managing stormwater at its source. To incorporate these approaches into models, it is necessary to have a thorough understanding of the hydrological processes at play. These processes also have a significant influence on determining the water flow scheme. Moreover, water quality is closely connected to the movement of pollutants. The processes of the movement of pollutants are influenced by the hydraulic conditions within the network of watercourses.

One issue in the current hydrological model is that it is hard to work at the scale of a town and none model treats the energy balance. If we focus on the scale of the modelling, we can detect one factor that is really different from natural watershed and cities. Indeed, in natural environment, the subdivision is done in watershed. But in city environment, the subdivision is done following the sewage system. In cities, the limits have to be good defined. The administrative limits are not really pertinent with respect to the hydraulics limits. The main trouble with the sewage system is that it is interconnected. So, in city there are natural and urban flow. The first type of flow is the flow of the water through river or associated to the relief. This first flow allows us to determine a first catchment. Then, the sewage system is added and doesn't necessarily correspond to the natural watershed. The sewage system can be present under three forms : the wastewater system that transports domestic and industrial waters that contain pollutants, to the sewage treatments plants; the rainwater system that evacuates rainwater in the nature without any treatment; the unit system that transports both wastewater and rainwater to the water treatment plants. These different systems are connected together and it's the major deal for the modelization in urban area. One model that can present these three system is SWMM, the model used for this study.

2.3 Zoom on SWMM

Some studies are already done with the SWMM model. A lot of these studies present cases where the drainage system is not well designed and explain which solutions work the best. An evaluation of the drainage system in Iraq by Nile and al. [17] showed that the drainage system is not able to drain all the rain water. Some solutions were proposed : increase the diameter of the pipes, add a new line in the drainage system or increase the percentage of green surface. All these solutions are common mitigation solutions. Here, after having modeled on SWMM, they conclude that add a new line allows to decrease the floods from 48 % to 33 % under a rain of 33.5 mm/h. Another study about Iraq was done by Mohammed and al. [16] shows that the drainage system works well under dry conditions but when there is a big event of rain, some locations were flooded. The solution is also to add two new sewer lines. A study about Iran, written Babaeia and al. [5] presents that SWMM tends to underestimate the peak runoff. In this study, they also explain that the runoff increases with the percentage of imperviousness. So, it is really important to define which subcatchments are the most critical and which junctions are the most surcharged. When we know these two critical points, it is easier to size all the drainage system. In this drainage system, the capacity is

not sufficient to catch all the water without occurring floods. A solution is to put some Low impact development -LID-. About the LID, Xing and al. [30] displayed that to control stormwater and water supply, the LID solutions control make a huge difference. In China, they analyze the use of runoff storage and filtration in different layouts changing the parameters. Under underflow precipitation, the control efficiency of the total outflow is proportional to the percentage of imperviousness of the subcatchment where the LID is. But under high rain event, the control efficiency increases when the structure and volume of storage of the LID increase. It is important to notice that the efficiency of the mitigation solution depends on the different type of rain events. Another study done by Bai and al. [6] in China, analyzes the effect of different LIDs. The four situations analyzed : without any LID control, with a LID infiltration, with a LID water storage and with the two LIDs. In general, the combined solution, water storage + infiltration, works the best to decrease the peak flow and the volume of flood. Depending on the situation of the different LIDs, they have different impacts. They note that for some locations on the drainage system, infiltration can be really performing but water storage can have no impact. When the rainfall increases, the reduction rate of runoff decreases. Apart from all the studies area where the drainage system is not well sized, in India, Ahamed and al. [24] demonstrated that the drainage system in Vijayawada is well designed, and even more sufficient for extreme rainfall events. If we look at studies that are near to us, Rio and al. [20] studied the impact of pervious pavement and disconnected rooftop at Montpellier in France. The rooftop disconnection implies to transfer the runoff to pervious areas while pervious pavement were impervious surfaces transformed to pervious surfaces. These two mitigations allow to decrease the runoff volume and the pollutant load. In SWMM, they notice to be careful, because the LID model is not always appropriate to model some mitigation solutions. That's why they decide to not use it. They show that the land cover has a big impact on the percentage of runoff and the pollutant load transport. The main solution is to transform car park and pedestrian areas into pervious surface. Another observation is that the biggest decreased of the runoff happens when the rain has the most little return period. All these studies show that the SWMM software is widely used for the study of urban area especially to assess the runoff and the transport pollutant with different storm events.

Chapter 3: Hydrological modeling of urban area with SWMM

3.1 Introduction

This chapter is written from the SWMM-User's manual [28]. SWMM - Storm Water Management Model - is a dynamic rainfall-runoff simulation model that provides the volume and quality of runoff in urban areas. SWMM is used to represent a drainage system. This representation is made of water and material flows between different major environmental compartments. The different compartments are composed to the atmosphere that generates precipitations and pollutants deposits. This goes to the land surface compartment, represented by a subcatchement, and this compartment sends outflow in three forms. The three forms of the outflow is infiltration to the groundwater compartment, surface runoff and pollutant loading to the transport compartment. The groundwater compartment gives a part of the infiltration into the transport compartment that is a network transporting water to outfall or treatment plans. The model assesses the runoff and the pollutant loads produced from rainfall on sub-catchment areas. After having determined the runoff, SWMM's routing component transports the runoff through channels, pipes, pumps, storage, and treatment devices. The program monitors the amount and quality of the runoff in each subcatchment, as well as the flow rate, and depth of water flow in each pipe or channel during the simulation period.

SWMM was developed in 1971 and is still widely used for planning, analysis and design of stormwater runoff, sanitary sewers, combined sewers, and other drainage systems in urban as well as non-urban areas.

3.2 Representation of the system

As said before, SWMM is a semi-distributed model. So, we can divide a study area into as much as needed irregular subcatchements in order to fit the effect of the spatial variability of different parameters on the runoff generation. These parameters are topography, drainage pathways, land cover and soil characteristics. We can define an idealized subcatchement as a rectangular surface with an uniform slope and a width that drains to a single outlet channel. In general, the subcatchements boundaries allow to have a sub-area with a flow path that has a common direction and drains the same outlet. Each subcatchement is divided into three subareas with or without depression storage : an impervious area with depression storage, an impervious area without depression storage and a pervious area with depression storage.

The input parameters defining the hydrologic characteristics of a subcatchement:

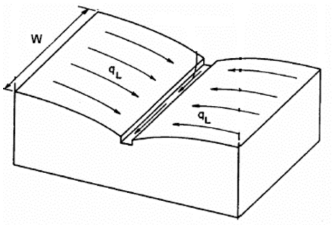


Figure 3.1: Representation of a subcatchment. [27]

- Area A : The area of the subcatchement that is defined by the boundaries.
- Width W : The area of the subcatchement divided by the length of the longest water overland flow path. When there are different possible flow paths, we can use the average of the lengths. We have to be careful to not take into account the flow path through channelized flow. In non-urban areas the width has to be smaller than 150 meters (500ft). Indeed, in natural environments, the real overland flow can only persist for 150 m before it consolidates into rivulet flow. Sometimes it is really difficult to identify all the flow paths. So, we can use this input as a calibration input in order to have a runoff hydrograph similar to the observed one.
- Slope S_0 : The slope over which the runoff flows through the flow path or the area-weighted average of the different slopes of the different flow paths in the subcatchement. The same slope is used for pervious and impervious surfaces.

- Imperviousness : The percentage of impervious areas through which rainfall can't infiltrate. We have to be careful with this parameter. It can be deduced from measures in fields to determine the impervious area draining directly to the stormwater system. We can use the runoff coefficients because it overestimates this parameter, so it is on the safe side.

- Roughness coefficient n : The Manning's roughness coefficient that describes the amount of resistance of the runoff flow in the subcatchement area. The roughness coefficient is different for pervious and impervious surfaces, and the pervious one is generally an order of magnitude higher than the impervious one.

- Depression storage : The volume that needs to be filled before any apparition of runoff. Different values of depression storage can be used for pervious and impervious surfaces.

- Percent of impervious area without depression storage : Represents the immediate runoff due to the beginning of the rainfall before the depression storage is satisfied. By default, we use 25%.

The last input is the precipitation that is represented by a rain gage that is linked to a subcatchement. This rain gage describes the format and source of the rainfall input and can be used for more than one subcatchement. This rain gage is described by the rainfall data type we provide, the intensity, volume or cumulative volume and the recording time interval.

Now, since I will use a model that describes an urban area, I will introduce the properties of a drainage system. SWMM uses nodes connected by links that control the flow rate to represent a conveyance network. The links can be conduits, orifices weirs and pumps. The nodes are used to give more information about the conveyance system like the elevation and the time-varying hydraulic head. The flow that passes through the conduits goes to an outfall.

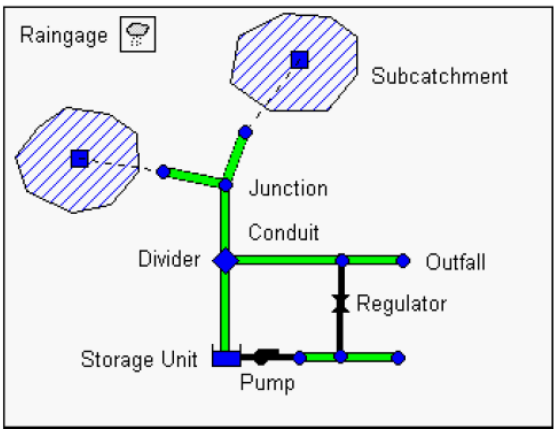


Figure 3.2: Representation of the flows in urban area. [28]

The nodes are divided into four categories :

- Junction nodes : Are nodes where the links join, or where the flow can enter in the system. The input parameter are the invert elevation of the channel or of the manhole bottom and the height to ground surface. The junction nodes can represent manholes or pipe connection or the points of change in the parameter of the links.
- Outfall nodes : Are the last nodes in the system, they represent the exit of the flow. They can only be connected to one link. The input parameters are the invert elevation and the type of outfall.
- Flow divider nodes : Are used when there are more than one exit of the node. They permit to divide the flow into two exit links. They are only active in Steady Flow and Kinematic Wave routing. The input parameters are the invert elevation, the type of divider, the junction parameters, the maximum depth. [1]
- Storage units : Are nodes providing storage volume. The input parameters are the invert elevation, the maximum depth, the storage curve. They can represent reservoirs as catch basin.

The links are divided into five categories :

- Conduits : Transport the flow from one node to another. They can have different cross-section, in appendix A.1. The input parameters are the inlet

[1]They are divided into four types : "the cutoff divider that diverts all inflow above a defined cutoff value; the overflow divider that diverts all inflow above the flow capacity of the non-diverted conduit; the tabular Divider that uses a table that expresses diverted flow as a function of total inflow; the weir divider that uses a weir equation to compute diverted flow."

and outlet node, the shape and geometry of the section, the length, the roughness, the inlet and outlet offset. The Manning equation is used for the relation of the discharge, with the flow rate Q, the cross-section area A, the hydraulic radius R, the slope S of the conduit :

$$Q = \frac{1.49}{n} A R^{2/3} S^{1/2} \tag{3.1}$$

- Pumps : Are used to lift water to higher elevation. The relation of the pump flow rate with respect to the condition at inlet and outlet node is described by the pump curve. The input parameters are the inlet and outlet node and the pump curve.

  The next links are flow regulators that control flows. Typically, they are used to regulate the discharge from storage facilities, mitigate any excessive surcharging that may occur, redirect the flow towards treatment facilities and interceptors.

- Orifices : Represent outlet and diversion structures, they can be used as storage units. The input parameters are the inlet and outlet node, the type of orifice, the shape and the geometry, the inlet offset and the discharge coefficient. They can represent openings in the manhole, storage facility or control gate. The flow is calculated as, with Q the flow rate, C the discharge coefficient, A the area of the opening of the orifice, h the head difference across the orifice :

  $$Q = CA\sqrt{2gh} \tag{3.2}$$

- Weirs : Are used as orifices but located across the channel or at the beginning of a storage unit. The input parameters are the same as for the orifices.

- Outlets : Are used to regulate outflow of storage units. The parameters are the inlet and outlet node, the inlet offset and the rating curve.

Once, all the model done, it's time for computation. There are different methods used by the software to model the result using some physical processes.

- Surface runoff : The inflow of each subcatchement, treated as non linear reservoir, comes from two entries. These two entries are the precipitations and the flow coming from upstream subcactchments. Considering the outflow, it will infiltrate, evaporate and the rest of water will runoff on the surface. The capacity of this "reservoir" is determined by the maximum depression storage (d_s), representing the maximum surface storage resulting

from ponding, surface wetting, and interception. When the water in the reservoir goes higher than the depression storage accepted, surface runoff appears.

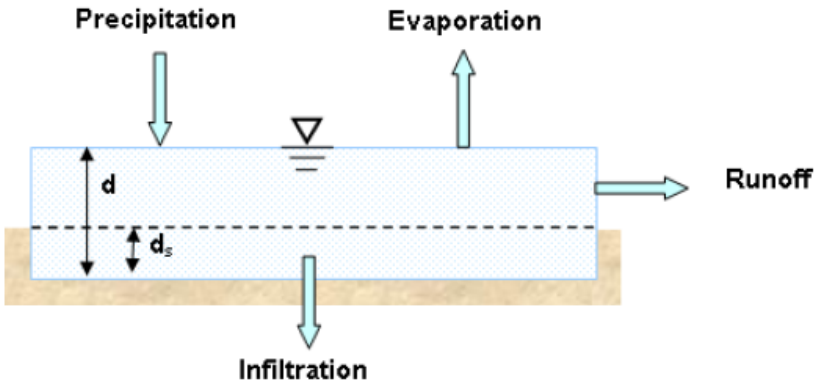


Figure 3.3: Flow of the water in the soil.[28]

- Infiltration : Is modeled in four different ways in SWMM. It represents the water entering the soil where the zone is pervious and unsaturated.
  - Horton : Comes from empirical observations. Over the duration of a long rainfall event, the process of infiltration experiences an exponential decrease, starting from an initial maximum rate and gradually reaching a minimum rate. The input parameters are the maximum and minimum infiltration rates, the decay coefficient and the time needed for a completed saturated soil to be completely dry.
  - Modified Horton : Uses a cumulative infiltration instead of time. It gives a better approximation when the rain is low. The input parameters used are the same as for Horton.
  - Green-Ampt : Says that a distinct wetting front is present within the soil column. The soil is separated in layers, with a saturated soil above and below this saturated soil there is an initial moisture content. The input parameters are the initial moisture deficit in the soil, the hydraulic conductivity of the soil and the suction head at the wetting font.
  - Curve Number : Is used for simplified runoff model. The total infiltration capacity ran out with time during rainfall. It decreases as a function of the cumulative rainfall and the remaining capacity. The input parameters are the curve number and the time for a completely saturated soil to be entirely dry. This is the model that I will use since there are a lot of data already existing and it is commonly used.

- Groundwater : Is defined with two zones in the SWMM model. The upper layer is a unsaturated zone, and the lower layer is a fully saturated zone with its moisture content that is equal to the soil porosity.

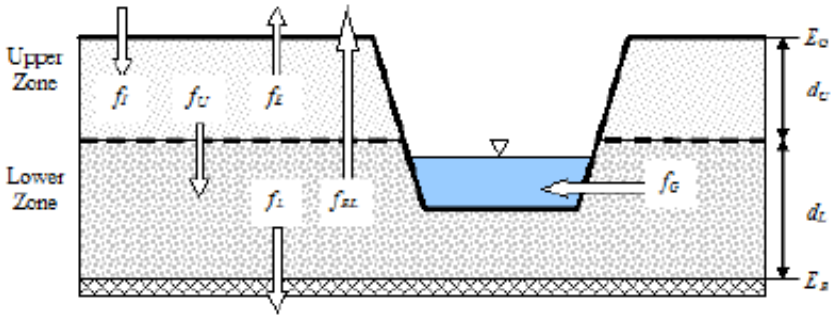


Figure 3.4: Groundwater model. [28]

- Flow routing : The equations that SWMM solves are the conservation of mass and the momentum equations for varied unsteady flow. These equations can be solved with different levels of accuracy. The Manning equation is used to express the flow rate in terms of flow depth and bed slope.

  - Steady Flow : Is the simplest routing. This routing takes each time step flow uniform and steady. So, the inflow hydrograph at the upstream goes to the downstream exactly in the same form without delay. The best use for this routing is for preliminary design to have an idea of the outflow. It doesn't take into account all the nodes that stores the water.
  - Kinematic Wave : Uses the momentum equation in each conduit to solve the continuity equation. To do this calculation, the water surface is assumed parallel to the conduit. The spatial and temporal variation is accepted for the flow and area in a conduit. The backwater effects, entrance/exit losses and pressurized flow are not taken into account. It is a good use for long term simulations.
  - Dynamic Wave : Is the most accurate routing because it solves the complete one-dimensional Saint-Venant flow equation. The advantage with this routing is that it supports pressurized flow, channel storage, backwater, entrance/exit losses. The time steps should be smaller than 30 seconds.

3.3 Running a simulation

In order to run a simulation, a lot of things has to be described, it can be done in the category Options. There are five panels with different options :

- General options :
  - The process models : Are there if some special elements need to have a simulation of their process. For example : if there is an aquifer or groundwater element, we can make the simulation with groundwater on and off to see the difference. If none special element is present, there is no need to check a box. In our case, we only need the box Rainfall/Runoff and Flow Routing in order to simulate the urban area.
  - The infiltration model : Is the model selected by default to the infiltration of the rain into the upper soil of the catchment. These models are already described in the section 3.2 at page 41. As already said, I will use the Curve Number infiltration model because some data are available, in appendix B.1.
  - Routing model : Is the model used for the flow route through the sewage system. These models were already discussed in the section 3.2 at page 42.
  - Routing options : We can check the option "Allow Ponding". It will allow excess water on nodes and its reintegration into the system when the conditions enable it. To permit ponding at a specific node, it is necessary to assign a non-zero value to its "Ponded Area" attribute. The "Minimum Conduit Slope" is by default on zero, that means no minimum is imposed. But if we want to impose a minimum value of the slope of the conduits we can put a number (%).

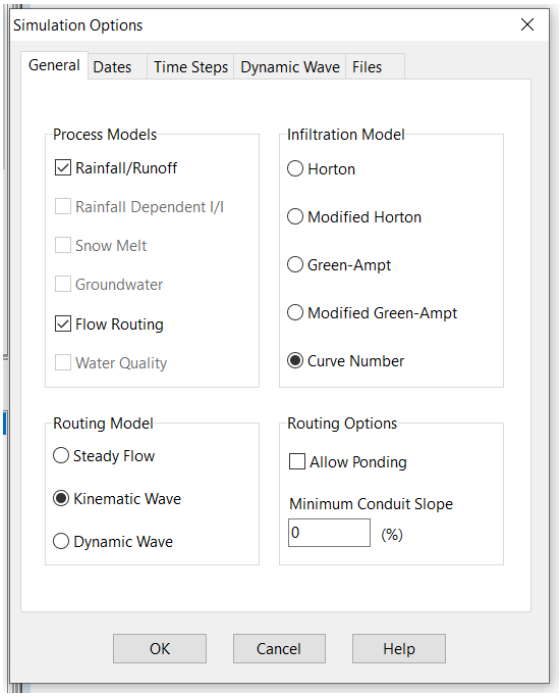


Figure 3.5: General simulation options. [EPA SWMM]

- Dates : We can determine the date and time of the start and end of the analysis and the report, and the number of antecedent dry days.

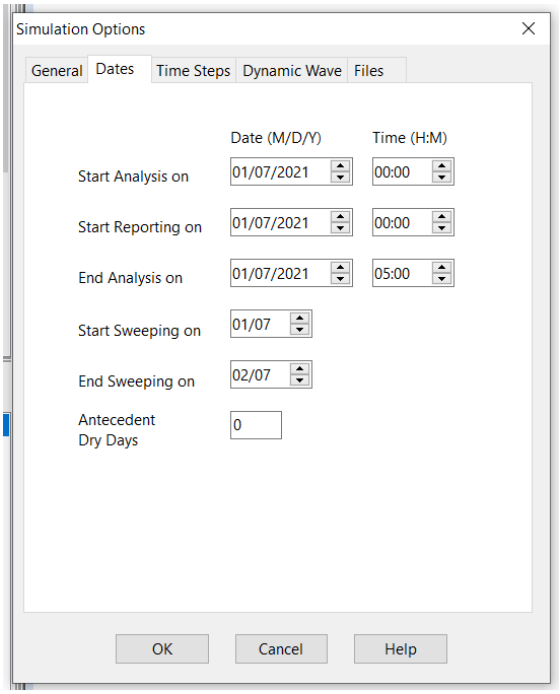


Figure 3.6: Dates options. [EPA SWMM]

- Time steps :
  - Time steps : We can define the time steps for the runoff, routing computation and the results reporting. The ”Runoff Step : Dry/Wet Weather” are used for the runoff calculations during, respectively, the periods of no rainfall and rainfall, without ponded water and with ponded water remaining on the surface, with LID controls dried and with LID controls infiltrating or evaporating runoff. The time step of the ”Dry Weather” has to be greater or equal to the one of the ”Wet Weather”. The ”Control Rule Step” is defined by default, that means the control rules are checked at each routing time step. The ”Routing step” is the time step for the routing flow and water quality.
  - The ”Steady Flow Periods” : Describes the behavior on the periods where the hydraulics of the system stay constant and doesn't change over time. The system is under steady flow period if the difference between total system inflow and total system outflow, in percentage, is smaller than the System Flow Tolerance and if the differences between the current lateral inflow and the one from all the previous time step at all points in the sewage system, in percentage, are smaller than the Lateral Flow Tolerance. If we check the ”Skip steady Flow Periods”, when in periods of Steady Flow, SWMM will use the most recent system flow in the system calculated.

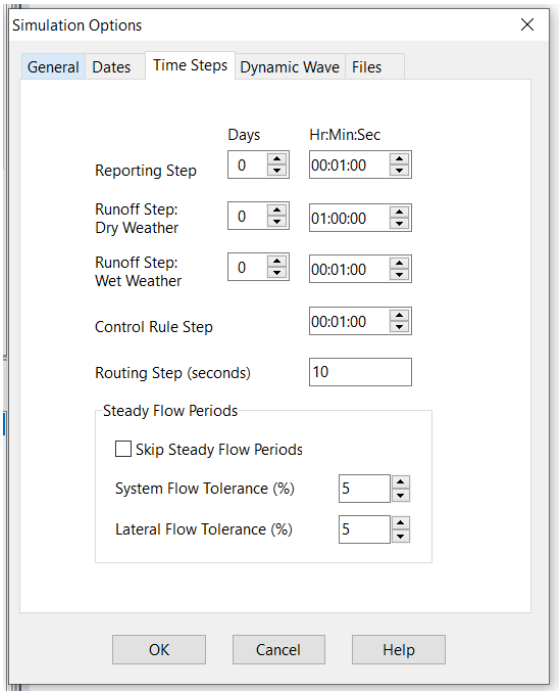


Figure 3.7: Time steps options. [EPA SWMM]

- Dynamic Wave : Describes all the parameters controlling the dynamic wave flow routing. Here, all the default parameters will be used.
  - Parameters : The "Initial Terms" describes the initial terms in the St.Venant momentum equation : "Keep" they heave their full value under all conditions -"Dampen" they are reduced when the flow is close to a critical flow and ignore them with a supercritical flow - "Ignore" they are not included in the momentum equation; "Normal Flow Criterion" determines when a supercritical flow occurs in conduits : "Slope" when the water surface slope is higher than the slope of the conduit - "Froude no." when the Froude number is bigger than 1 - "Slope & Froude" uses the two criteria above and it is the recommended choice - None ; "Force Main equation" is the equation used to compute the friction losses when there are pressurized flow for a Circular Force Main cross-section : "Hazen-Williams" or "Darcy-Weisbach" ; "Surcharge Method" describes the behavior under surcharge conditions : "Extran" uses a variation of the Surcharge Algorithm in order to update nodal heads during the fullness of all the connecting nodes - "Slot" allows to use the normal procedure during full pipe using Preissmann slot that add a small virtual top surface width to pipes that are full.

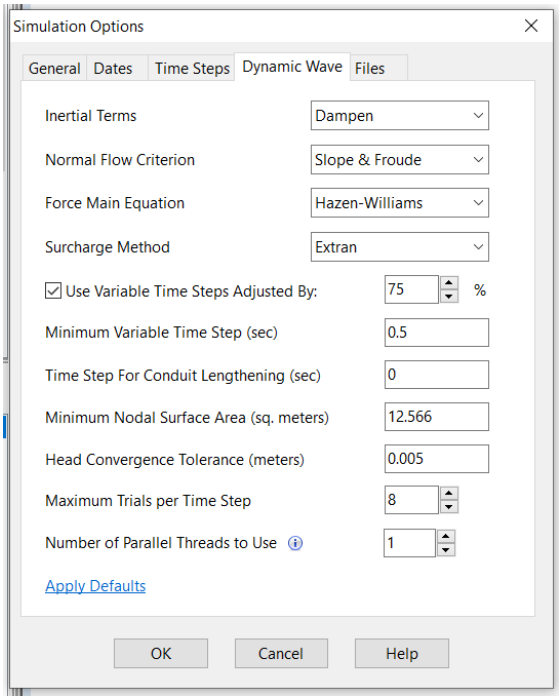


Figure 3.8: Dynamic waves options. [EPA SWMM]

- Files : We can specify which files will be saved or used during the simulation.

Chapter 4: Study of the Espierres watershed

4.1 Site history

The Espierres is a river taking its source in France, in the European metropolis of Lille at Roubaix, and flowing down into the Escaut at Espierres-Helchin in Belgium. The length of The Espierres is 16km. During its journey, the Espierres is reached by various tributaries, including the Petite Espierres and the Grande Espierres. The Petite Espierres takes its source at Neuville-en-Feurain in France, follows the Franco-Belgian border and enters the Espierres at Ballons. Meanwhile, the Grande Espierres takes its source at Mouscron in Belgium and enters the Espierres at Boisquet-Clache.

We will focus on the watershed of the Petite Espierres, the main problem of this river is the water quality. From the Boix Fichaux to the water treatment plant of Mouscron, the Petite Espierres is a collector. It serves the purpose of gathering wastewater and rainwater from the surrounding area. There has been a debate regarding the replacement of the combined function of the Petite Espierres, an abandoned structure due to its high cost. Consequently, there are no plans to establish a separate sewage system exclusively for the pipes leading to the water treatment plan of Mouscron. The Petite Espierres has served as a collector for a considerable period. However, until 2013, it was an open-air collector, prompting its enclosure due to unpleasant odors. Another crucial aspect to take into account is the use of a material known as 'mâchefer' during street renovations, which is made from sewage treatment. Unfortunately, this material is incompatible with water, rendering it entirely impermeable.



Figure 4.1: Espierres. [Google Maps]

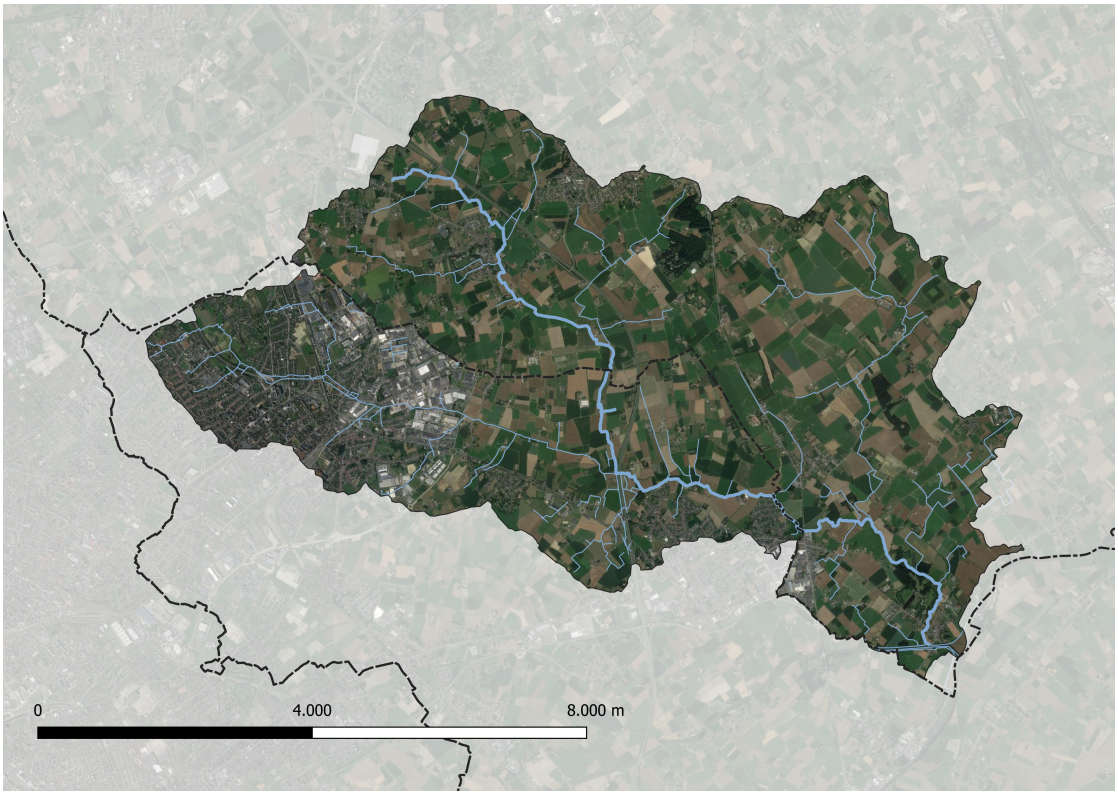


Figure 4.2: Watershed of the Grande Espierres and the Petite Espierres. [QGIS]

4.2 Zoom on some particular places

Although a part of the watershed is located in the Flemish part of Belgium, we will only consider the Walloon part. The data don't coincide exactly between the two regions and the part in the Flemish region is so small that it can be negligeable in this study. The watershed of the Petite Espierres is a fairly flat terrain with a relatively little constant slope. In contrast to the catchment area of the Grande Espierres, the catchment area of the Petite Espierres is predominantly urban. Indeed the surface of the Grande Espierres is mostly covered by fields. While the surface of the Petite Espierres is mostly filled with residential, such as houses (in black) 2 facades with garden, in the left part of this area. On the right, the surface is entirely covered by fields (in yellow). The fact that the watershed of the Petite Espierres is covered with housing allows for a study to be done in an urban environment and not in a natural environment. So, this is why this study will be focussed on the Petite Espierres. Moreover, as the watershed of the Petite Espierres has a surface area of 14.3 km^2, it may be wise to focus on some specific places. Indeed, if I propose improvement system very localized, it won't have a really big impact on the flow that will go out the watershed. But at this localized place, it will improve mitigate floods or it will increase the infiltration in order to reduce the runoff. These localized solutions have a noticeable impact at the scale of a street for example. This is why I will focus on two different localized places on this study.

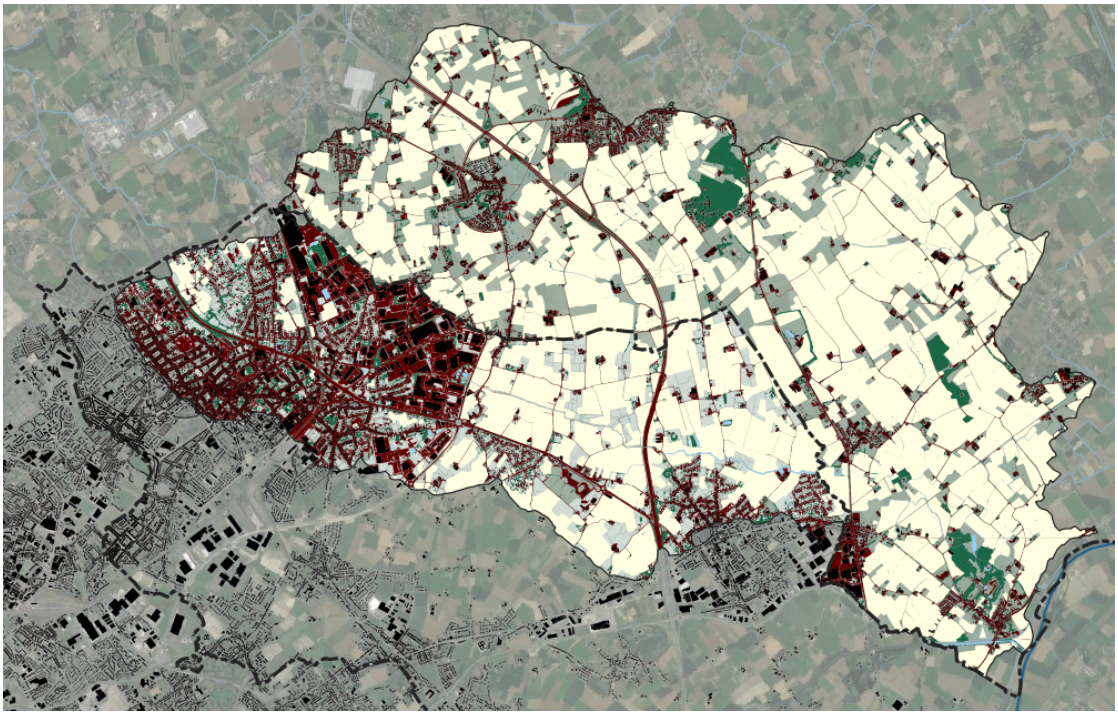


Figure 4.3: Watershed and land use of the Grande Espierres. [QGIS]

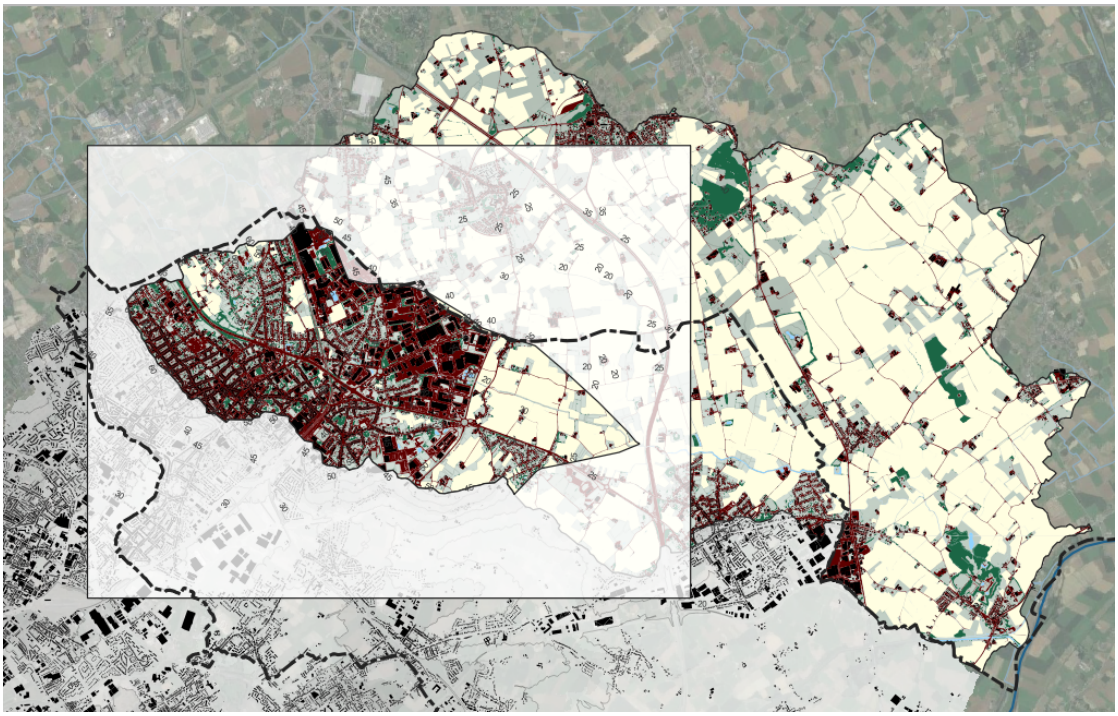


Figure 4.4: Watershed and land use of the Petite Espierres. [QGIS]

The first location is the Rue du Nouveau monde (in red). This street is situated at the west of the watershed and is 1.5 km long. This street is regularly flooded by overflowing sewers. In this location, I will study a way to stock the rainwater

in the road or how to decrease the runoff that arrives to this street with other methods.

The second location is the Ferme de la Blommerie (in yellow) that is nearly situated at the middle of the catchment of the Petite Espierres. At this place, the sewage system often overflowed. However, the sewage system only carries wastewater. Since a check valve have been installed, there is no problem anymore. This check valve avoids rain water flowing in a downstream collector to enter into the wastewater collector. This means that the rain water collector is not well sized for the runoff coming at the inlet point. So about this place, I will only study the watershed of the inlet where the rainwater enters. I will check some methods to retain water in the soil and avoid water to go in the rain water sewage.



Figure 4.5: Watershed and particular places of the Petite Espierres. [QGIS]

4.3 Modeling steps

In order to can determine which type of solutions are efficient or not, I have to do model on SWMM. I will explain the procedure that is exactly the same for the two different locations.

1. Watershed : First of all, I have to determine the watershed. So, in this study, I work on the watershed of the Petite Espierres. The watershed will

be determined based on the topography and so on the natural flow path of the water.

2. Catchment : Based on the watershed and on the particular zones that will be studied, I can now determine the catchment to put on SWMM. Taken into account the sewage system and the natural topography, I look at the street or the local point where floods occur and I take all the area draining this particular place.

    - Boundaries : To determine precisely the catchment, we have to go through different steps. First, we have to determine what is the particular place considered. So, there are two different scenarios that can occur. The first one is that the flood occur at a local point, that will be the only outfall of the catchment. It is an urban zone that is treated, I have to look first at the flow entering from the sewage system to this point. Next, I look at which rainwater enters to the sewage system. This gives the combination of the sewage system and a kind of watershed to the sewage system. The second option is a street that is flooded. Normally, in the street there is a linear sewage system that passes through. So this sewage will be the termination of the catchment. But if the street has different exits, there will be more than one outfall. So, the first step is to determine all the outfall and then to do the combination of the sewage system carrying water to the street and the watershed of this sewage system.
    - On SWMM : Once the boundaries determined, we can draw the catchment on SWMM. To do this, it is important to import the image background with a file containing the coordinates of the background. Once the background put on SWMM, I can draw the catchment based on the boundaries determined previously. When the catchment is drawn, I have to put all the parameters of the catchment. As a reminder, the different parameters are the area, the width, the slope, the imperviousness, the roughness coefficient, the depression storage and the percent of impervious area without depression storage.

      For the area A, SWMM has a tool that calculates its by itself. For proper operation, it is important that the option Auto-Length is on and the flow units are in the good system (CMS is for the units in the international system).

For the width W, it is a parameter that we have to determine from the flow path. A point where I need to be careful is that the flow path can't exceed the length of 156 m. Because here we work with only one catchment, we have the find an equivalent flow path. So, the equivalent flow path L is based on the sum of flows paths from different zones that have the same one. It gives :

$$L_{eq} = \frac{\sum L_i A_i}{A_{tot}} \tag{4.1}$$

Since the equivalent flow path is calculated, we can find the width :

$$W = \frac{A_{tot}}{L_{eq}} \tag{4.2}$$

For the slope S_0, as this is the catchment, we also have to find an equivalent slope for the catchment, it follows the same principle than for the flow path. We divide the catchment into different zones with the same slope and calculate the equivalent slope :

$$S_{0_{eq}} = \frac{\sum S_{0_i} A_i}{A_{tot}} \tag{4.3}$$

For the imperviousness I, it can be deduced from an observational method. Indeed, it represents the percentage of surfaces that are totally impervious. It is different from the runoff coefficient but for some models it is easier to use the runoff coefficient C, that is the percentage of rainfall that will not be infiltrate and so runoff. When using the runoff coefficient instead of the percentage of imperviousness, it tends to overestimate the runoff discharge. It is due to the fact that the use of the coefficient runoff leads to a bigger estimate of the impervious area because it takes into account the runoff in both pervious and impervious zone. The real runoff coefficient will be recalculated in SWMM. To determine the runoff coefficient, there are different tables that regroup the runoff coefficient according to different parameters such as the land cover, the land use, the type of soil, presented on appendix C.1, C.2, C.3.

So, as we work on one catchment, we have to find the equivalent runoff

coefficient calculated by using the same procedure as for the other equivalent parameters. We divide the catchment into zones that have the same land use and calculate the equivalent runoff coefficient :

$$C_{eq} = \frac{\sum C_i A_i}{A_{tot}} \tag{4.4}$$

with : $\approx I \simeq C_{eq}$

For the roughness coefficient, we take the roughness coefficient that is the most present in the zone. Some tables are available to find the roughness coefficient, see appendix D.1.

For the depression storage, We take the most present depression storage. A classification is done as :

Land use	Depression storage [mm]
Impervious surfaces	1.27 - 2.54
Lawns	2.54 - 5.08
Pasture	5.08
Forest litter	7.62

Table 4.1: Depression storage. [28]

Once all the parameters of the catchment are assigned, we have to define the outfall of this catchment and put the outlet of the catchment as the outfall. Another parameter needed for the catchment is the rain gage that is defined depending the rain that we want to observe.

- Hyetograph from IDF : SWMM needs a hyetograph, that is the graph of the precipitation with respect to time, as entry for the description of the rain gage. Bu the IDF is the only data available : a double-entry table with the duration of the rain and the return period in number of years as parameters and it gives the quantity of rain in millimeters. We have to transform this quantity of rain in a rain intensity with respect to time.

Durée	Période de retour (années)											
	2	5	10	15	20	25	30	40	50	75	100	200
10 min	7.5	10.8	13.3	14.8	15.9	16.8	17.5	18.7	19.7	21.5	22.8	26.3
20 min	10.8	15.5	19.0	21.1	22.7	23.9	25.0	26.7	28.0	30.6	32.5	37.4
30 min	12.8	18.6	22.9	25.5	27.5	29.0	30.3	32.4	34.0	37.2	39.5	45.5
1 h	15.9	22.1	26.8	29.6	31.7	33.4	34.8	37.0	38.8	42.2	44.7	51.0
2 h	18.9	26.0	31.3	34.5	36.8	38.7	40.2	42.7	44.7	48.5	51.3	58.4
3 h	21.0	28.9	34.7	38.3	40.8	42.9	44.6	47.4	49.6	53.8	56.9	64.7
6 h	25.3	33.6	39.7	43.3	46.0	48.2	50.0	52.8	55.1	59.4	62.6	70.7
12 h	30.8	40.7	48.0	52.4	55.6	58.1	60.3	63.7	66.4	71.5	75.3	84.9
1 j	37.6	48.9	57.1	62.0	65.5	68.3	70.6	74.2	77.2	82.6	86.6	96.5
2 j	47.2	60.7	70.2	75.7	79.7	82.8	85.3	89.4	92.6	98.6	102.9	113.5
3 j	50.0	64.3	74.1	79.8	83.9	87.1	89.7	93.8	97.1	103.1	107.4	117.9
4 j	54.2	69.4	79.7	85.7	90.0	93.3	96.0	100.3	103.6	109.8	114.2	124.9
5 j	61.5	77.8	88.8	95.2	99.7	103.2	106.0	110.6	114.1	120.5	125.1	136.3
7 j	70.6	88.3	100.1	106.9	111.6	115.3	118.3	123.1	126.8	133.5	138.2	149.8
10 j	83.8	103.4	116.4	123.8	128.9	132.9	136.2	141.2	145.2	152.3	157.4	169.6
15 j	101.5	124.4	139.4	147.8	153.6	158.1	161.8	167.5	171.9	179.8	185.4	198.8
20 j	118.2	144.8	162.1	171.7	178.3	183.4	187.6	194.0	199.0	208.0	214.2	229.2
25 j	125.6	154.0	172.2	182.3	189.3	194.6	198.9	205.7	210.9	220.1	226.6	242.0
30 j	147.3	177.9	197.4	208.2	215.6	221.3	225.9	233.0	238.5	248.3	255.1	271.2

Figure 4.6: IDF table.[26]

The method used to transform the IDF values into a hyetograph is the Chicago method. This method produces a symmetric hyetograph. Firstly, the return period and the duration of the rain are chosen . The next step is to copy the data, for the return period, above the duration chosen in another table and transform the precipitation into an intensity of rain. To do this, the precipitation is divided by the duration of the first colon in hour. So, it gives the intensity of the rain for each rain duration. Here an example for the return period of 10 years and a duration of 2 hours.

Duration	in h	in min	10,0
10 min	**0,166**	**10**	13,3
20 min	**0,333**	**20**	19,0
30 min	**0,5**	**30**	22,9
1 h	**1**	**60**	26,8
2 h	**2**	**120**	31,3

Table 4.2: Precipitation [mm].

Duration	in h	in min	10,0
10 min	**0,166**	**10**	79,8
20 min	**0,333**	**20**	57,0
30 min	**0,5**	**30**	45,8
1 h	**1**	**60**	26,8
2 h	**2**	**120**	15,7

Table 4.3: Intensity [mm/h].

The next step is to find the difference in terms of intensity between each duration of the rain. Indeed, the precipitation of the rain for 20 minutes includes the precipitation of the rain for 10 minutes. So the 10 minutes added to reach the 20 minutes have a different intensity. The subtraction of the second intensity from the first intensity gives the difference of intensity between the two rains. The result for the precipitation and the intensity :

Duration	in h	in min	10,0
10 min	**0,166**	**10**	13,3
20 min	**0,333**	**20**	5,7
30 min	**0,5**	**30**	3,9
1 h	**1**	**60**	3,9
2 h	**2**	**120**	4,5

Table 4.4: Δ Precipitation [mm].

Duration	in h	in min	10,0
10 min	**0,1666667**	**10,000**	79,8
20 min	**0,3333333**	**20,000**	34,2
30 min	**0,5**	**30,000**	23,4
1 h	**1**	**60,000**	7,8
2 h	**2**	**120,000**	4,5

Table 4.5: Δ Intensity [mm/h].

Then, choosing the interval of time to put on SWMM, smaller or equal than the first duration of rain present in the IDF table, allows to create a table with the necessary entries. If we consider a rain of 2h, we will have 24 intervals of 5 min. The main goal is to determine the intensity for each of these 5 min interval. For the ease of the creation of the table, there are two different columns for the time, one form 0:00h to 02:00h and the other one from -01:00h to 01:00h. The table is filled beginning by the middle, this means from -00:05 h to 00:05 h with the intensity of the rain for the duration of the rain of 10 min. Then the table is fulfilled with the Δ intensity of each slot. This gives :

Time [hour:min]	Time	Intensity
00:05	-01:00	4,5
00:10	-00:55	4,5
00:15	-00:50	4,5
00:20	-00:45	4,5
00:25	-00:40	4,5
00:30	-00:35	4,5
00:35	-00:30	7,8
00:40	-00:25	7,8
00:45	-00:20	7,8
00:50	-00:15	23,4
00:55	-00:10	34,2
01:00	-00:05	79,8
01:05	00:05	79,8
01:10	00:10	34,2
01:15	00:15	23,4
01:20	00:20	7,8
01:25	00:25	7,8
01:30	00:30	7,8
01:35	00:35	4,5
01:40	00:40	4,5
01:45	00:45	4,5
01:50	00:50	4,5
01:55	00:55	4,5
02:00	01:00	4,5

Table 4.6: Hyetograph [mm/h].

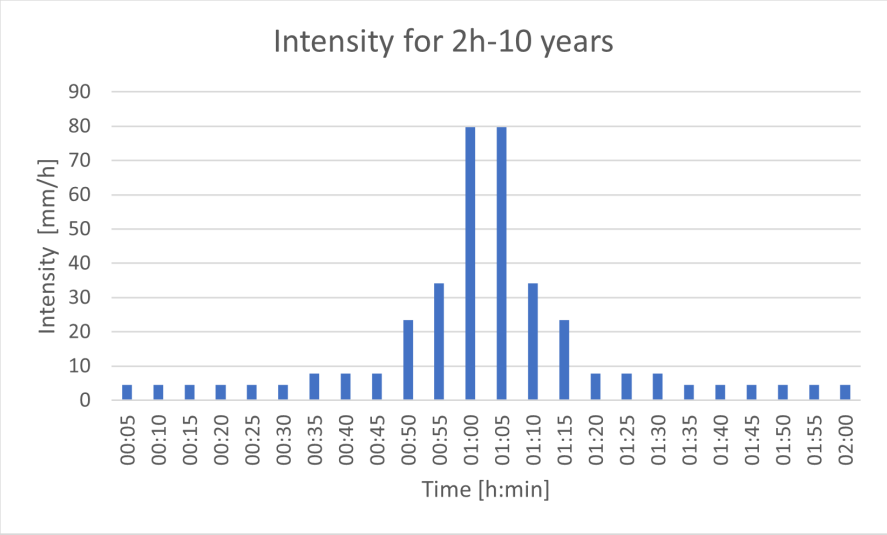


Figure 4.7: Hyetograph for a duration =2h and a return period = 10 years.

- Rational method [1] : To have an approximation of the maximal discharge expected, we can use the rational method. The rational method is a method that estimates the maximum discharge for a rain of a duration t_r equivalent to the concentration time t_c of the catchment with an intensity i constant over time.

  I will briefly explain the link between a rain event and the discharge that will go out from this rain. An uniform event of rain is characterized by its intensity and duration. So, the rain falls with a certain intensity i during a certain time t_r, this rain will fall to a catchment that has some pervious properties. It means that a part of the precipitation will infiltrate on the soil, there will be some superficial detention but also some storage in depressions. It means that not all the precipitation will be converted into runoff. So, the part of the rain that will run off to the surface, will produce discharge going to the outlet of the catchment.

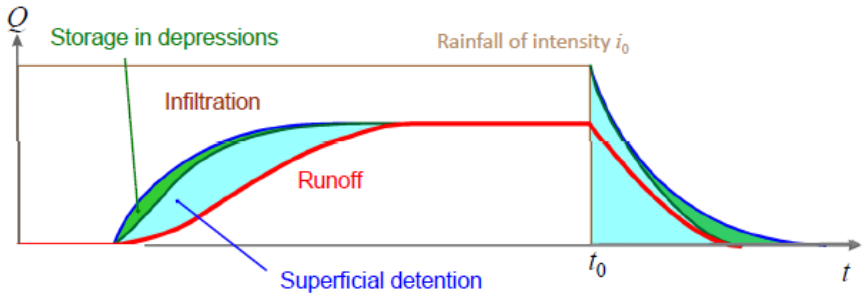


Figure 4.8: Distribution of the precipitation. [25]

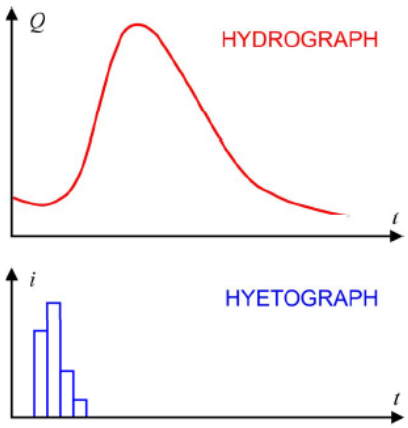


Figure 4.9: Hydrograph and hyetograph. [25]

[1] This section is written from the course Applied Hydraulics given by Soares Sandra [25]

Here the different steps of the contribution of the catchment during rain. The concentration time of a catchment is defined as the moment where all the drops water will participate to the discharge.

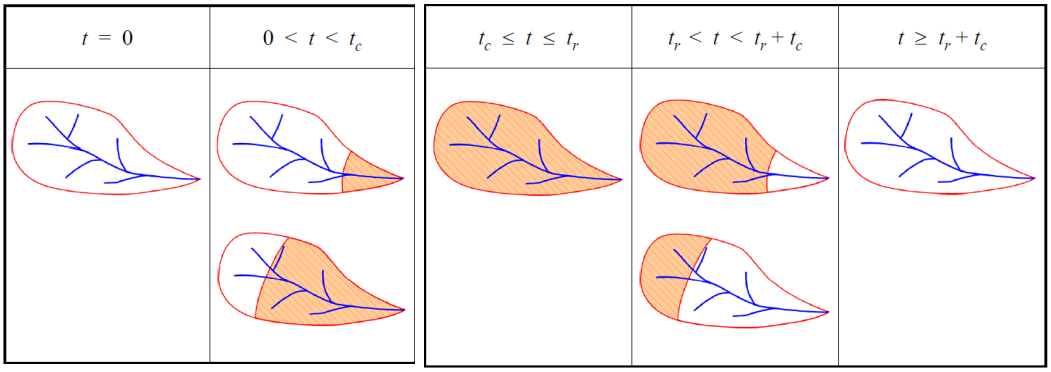


Figure 4.10: Contribution of the rain in the catchment.[25]

- $t = 0$: The rain hasn't started.
- $0 < t < t_c$: The rain began and the contribution of the catchment increases with time.
- $t_c \leq t_r$: The concentration time is reached and the rain is still falling. It means that all the catchment contributes to the discharge until the rain stops.
- $t_r < t < t_r + t_c$: The rain stopped, so the part of the surface contributing to the discharge is decreasing in the opposite way than it increased at the beginning.
- $t \geq t_r + t_c$: The time is greater than the sum of the concentration time and the duration of the rain is up. So, none water runs to reach the outlet, and the situation is the same as at time 0 before the rain.

Now understanding the theoretical hydrograph shape during an event of rain, it is easier to interpret the hydrograph shape. The further the zone is, the longer the water will need to reach the outlet. Depending on the duration of the rain, the time where discharge will occur will also vary. Depending on the temporal distribution of the intensity of the rain, the hydrograph will have different shapes. So, subject to the duration and distribution of the rain, the hydrograph representing the discharge at the outlet will have different shapes. Here, we can see a typical hydrograph, and see that there is a lag between the peak discharge and the rain, what is due to the time of concentration.

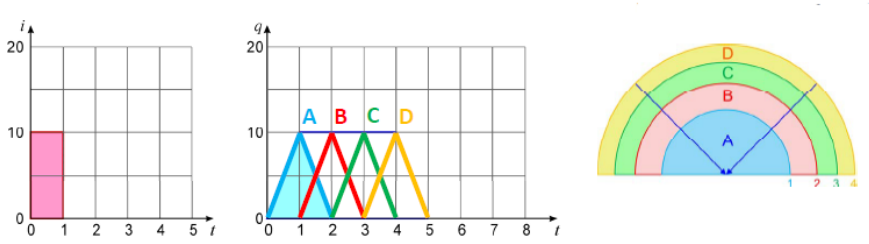


Figure 4.11: Hydrograph and hyetograph. [25]

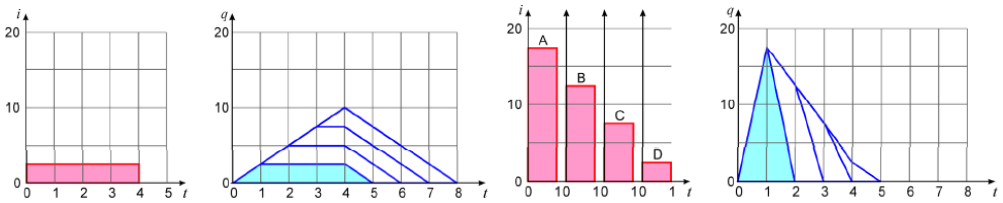


Figure 4.12: Hydrograph and hyetograph for different types of rain. [25]

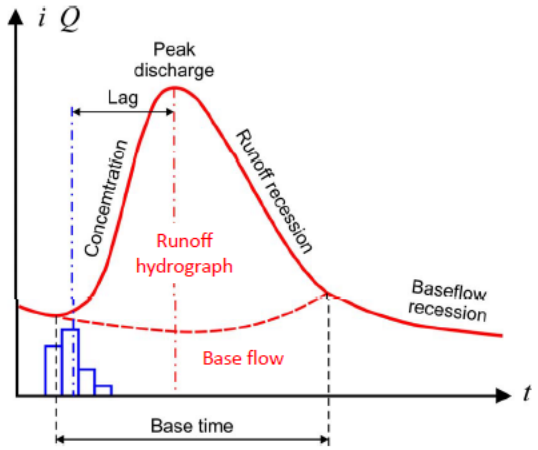


Figure 4.13: Hydrograph and hyetograph. [25]

The maximum discharge encountered during an event of rain is when the whole catchment contributes to the discharge. But to explain that all of the zones of the catchment contribute to the discharge, we have to describe how we divide this zone. One of the methods is based on isochrones. The isochrones are zones where the duration of the water travel is the same. So, it means that zones are divided regarding the time of flowing and not regarding length or so on. The time of concentration is equal to the product of the number of zones times the duration of travel of one zone. Using this method of isochrones

we only consider runoff coefficient equivalent to 0 or 1 corresponding respectively to no runoff or full runoff. Here we can see in terms of hydrograph.

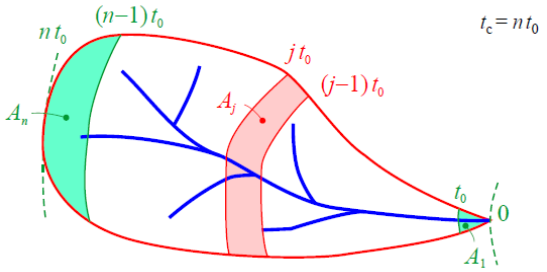


Figure 4.14: Isochrones. [25]

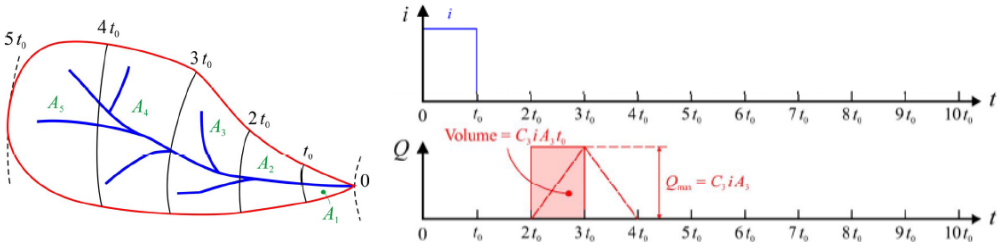


Figure 4.15: Isochrones, precipitations and discharge. [25]

If we consider a certain volume of rain, the maximum discharge is reached when the duration of the rain is equal to the time of concentration. Indeed, it means that at one moment all the catchment contributes to the discharge. If we consider a duration smaller than the concentration time, even if the intensity of the rain is bigger than for the maximum discharge, it means that at no time all the catchment contributes, so the maximum discharge reached for this rain is smaller than for $t_c = t_r$. For an event of rain with a duration bigger than the time concentration, it means that the intensity of the rain is smaller, even if all the catchment contributes during a time $t_r - t_c$, the discharge is smaller. We clearly see that the maximum discharge for a certain volume of water is reached when the duration of the rain is equal to the time concentration of the subcatchment. And this maximum discharge is calculated as :

$$\mathrm{Q_{max}} = \sum_{j=1}^{n} \mathrm{C_j i A_j} \tag{4.5}$$

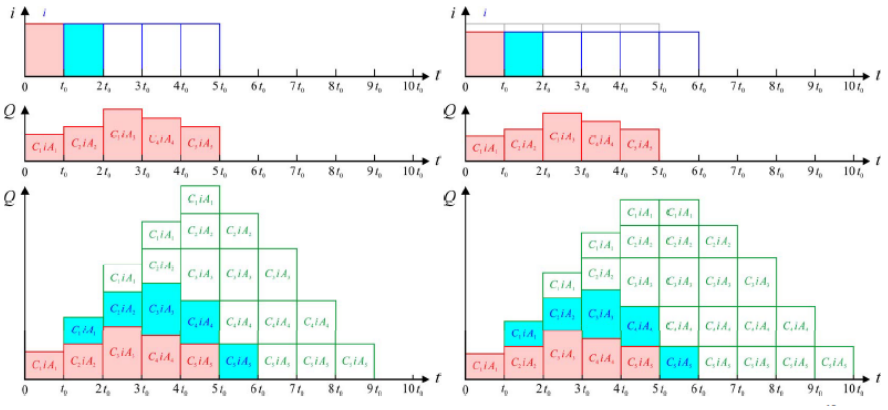


Figure 4.16: Hyetograph and hydrograph. [25]

In practical use, determining the isochrones is really difficult and time consuming, so it is not the method used. In general, the division of the catchment is done based on areas of equal runoff coefficient C. So, the catchment is divided regarding the land use and type of soil. We can now calculate the maximum discharge :

$$\mathrm{Q_{max}} = \mathrm{CiA} \tag{4.6}$$

with the total runoff coefficient calculated from the different runoff coefficient and area :

$$\mathrm{C} = \frac{\sum \mathrm{C_i A_i}}{A} \tag{4.7}$$

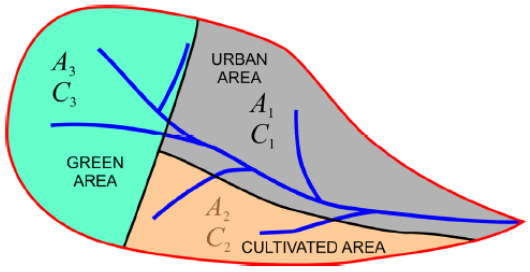


Figure 4.17: Division with the runoff coefficient. [25]

- Comparison between rational method and SWMM : Now, that we have calculated the theoretical maximum discharge, we can run a simulation on SWMM and see if this peak discharge corresponds to the one of the simulation. This step is important to determine if the model is well calibrated and all the parameters well determined. This step can be

done also further on the modeling, at each step to verify the accuracy of the discretization and the new elements.

3. Subcatchments : The software SWMM allows us to discretize the model at different scales. Since we had described the catchment, we can now, define the subcatchments. Indeed, here we have different options in order to define them. We can determine them according to the topography, so the natural flow and the land use. Or we can delineate them according to the sewage system. Since, we are on urbanized site, we have to take these two aspects into consideration. All the outlet of these subcatchments is the outfall of the global catchment. In reality, the outlet of each subcatchment will be the point where the water enters the sewage system. This first delimitation allows us to have an overview about the different flows paths and how the water flows. Of course, as long as we add new objects - subcatchments- we have to enter all the parameters. These parameters are defined the same way they were for the global catchment. Normally, we should have a total outflow that would be really similar to the outflow for the global system, as the global parameters should be equivalent to the discretized version.

4. Sewage system : Now we can add the sewage system.

   - Nodes : We define all the nodes of the system. We need nodes at the entries of the sewage system, when two junctions will connect, when there is a change in slope or diameter of the conduit. Defining these nodes means to place them on SWMM at the good place but also give information about all the input : the invert elevation, and the maximum depth of this node that correspond respectively the elevation of junction's invert and the maximum water depth - the distance from the invert elevation to the ground surface.
   - Conduits : We can connect the nodes with conduits. So, the conduits will go from one node to an other node. There is a main system, with the main conduit where all the other conduits will be added. The input parameters of the conduits are : the shape, here we use only circular conduits, so we have to define also their diameters, the length of the conduit calculated with the auto-length tool, and finally the roughness of the conduit, see appendix D.2.
   - Connection : All the sewage system having been already defined, we can connect the subcatchments with the sewage system. It means that the outlet of each subcatchment will no longer be the outfall of the

global catchment but will be one node of the sewage system which is the entry of the water coming from this subcatchment.

- Verification : We can run the same simulation as before and check that the outflow discharge is similar to the other one in order to check the accuracy and correctness of the sewage system.

5. Redefinition of the subcatchment if needed : As we have added the sewage system, we can now verify that all the subcatchments are well defined according to the entries of this sewage system. We can also go further and check if, in this subcatchment we can discretize more according to the needs of the simulation.

6. Simulation : The whole drawing is done and the last step is to run a proper simulation with the good parameters. We will run simulation with rainfall/runoff and flow routing checked. The infiltration model used is Curve Number and we use Kinematic Wave.

7. Analysis of the simulation : Once we have all the output of the simulation, we can analyze them. We have to check if at any point there is overflow, where the flow or depth water is the biggest. Also, I can do more than one simulation that allows to change the properties of the rain and see what are the impacts depending on the type and duration of the rain.

8. Mitigation : It is now time to propose some new solution. According to the previous results, looking which mitigation of floods are useful or not, and which one are the best for which place and which outcome that we want. It leads to different options in the public and private domain. The different solutions in the public domain are restricted since we look at urban area. The public domain means roads and municipal places. These solutions include the decrease of the imperviousness of the surface, draining trenches and filter strips along the roads and the last one is the reservoir. I will propose some solutions on the private domain, the green roof and tank reservoir. Of course, the diminution of impervious zones is applicable in the two domains.

    - Percentage of imperviousness : The first mitigation is to decrease the percentage of imperviousness of the watershed. It is an easy change in the model. Indeed, the only parameter to change is this percentage. It can be changed in some subcatchment or directly for all the subcatchments depending on the distribution of the land use in the watershed.
    - Low impact development LID : Are mitigation solutions operating on small scale. They are really influenced by the infiltration and the stor-

age. It reduces the overall runoff volume and can also control the water quality. In these low impact developments exist two different solutions : the infiltration trenches (IT) and the filter strips (FS). They are usually located along the road.

The filter strips are area covered by grass or plants. The runoff passes through these areas. These filter strips have a function of removing the particulate pollutants for event of small duration and intensity. They don't reduce a lot the peak discharge. Some different requirements are necessary for the good operation of the filter strips. The slope doesn't have to exceed 5 % and the natural subsoil should have a low to fair permeability that means a permeability between 0.15 to 4.3 mm/h. In SWMM, the filter strips are represented as 100 % pervious subcatchment where no rain falls. The runoff from the upstream subcatchment goes through the filter strips, this water runoff is drained to a conduit that represents the gutter or the street. In the simulation, infiltration and storage are the two main processes to simulate.

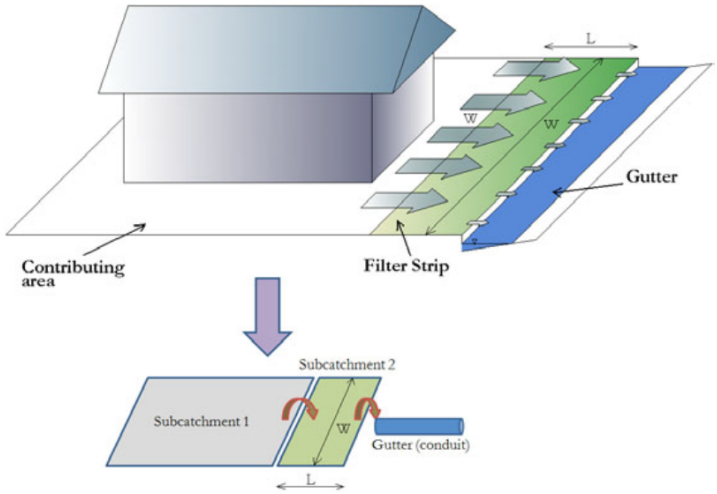


Figure 4.18: Schematic representation of filter strip. [27]

The infiltration trenches capture the runoff to infiltrate it to the ground. These trenches are excavated and then filled with stone aggregate. One requirement for the good operation of these trenches is a subsoil with a permeability bigger than 13 mm/h. During the simulation, the main processes are the infiltration, storage and water flow along the trench. In SWMM, a trench is represented as a 100 % pervious subcatchment with a depression storage depth which is equal to the pore space available in

the trench.

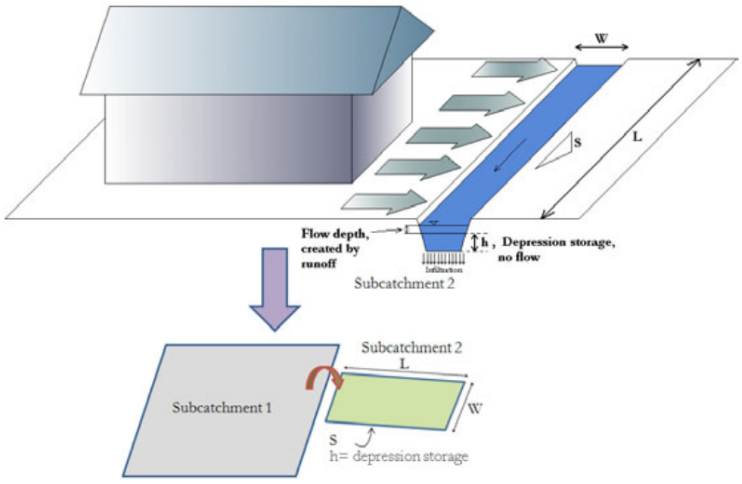


Figure 4.19: Schematic representation of infiltration trench. [27]

The definition of the length and the width is opposite for infiltration trenches and filter strips.

- Reservoir : when the runoff is too important, one solution is to store the water before it reaches the street and so the sewage system. One mitigation of floods is to forecast some spaces, on plots of house, where we put some water reservoirs. It exists two types of reservoirs : the retention pond and the detention pond. The detention pond is a basin that retains the water in a non permanent way and it is dried all the time except when there is important event of storm. In these critical events, this pond retains the water and releases it really slowly through a small exit. It allows to delay the peak discharge. The retention pond is a basin that is always full, it is its main function to store the water. In SWMM, to simulate the detention pond, we need three different elements, that are storage units, orifices and weirs. The storage units are nodes which the storage volume is described by a storage curve, we can specify an evaporation factor, and we have to define the maximum depth of storage. The storage curve describes how the water depth influences the surface area. The evaporation factor tells if evaporation from the surface of the storage unit is allowed (=1) or if the evaporation is ignored (=0). The orifices represent the opening of the storage unit that is an outlet.The orifice is between the storage unit and the downstream conduit. The weir represents the opening at the top of the storage unit that is an overflow structure.

- Green roof : In the private area, one solution is to build houses with flat green roof. The flat green roof allows to store water in order to delay the peak discharge. In SWMM, some parameters for the subcatchment representing the house has to be changed.

4.4 Proposed solutions and outcomes

For the modeling of the two sites, different rains are used : duration of rain t_r 10 minutes for the return period T_r of 2,10 and 25 years and the duration of 2 hours for the return period of 10 and 25 years, see appendix E.1 and E.2.

4.4.1 Rue du Nouveau Monde

As said before, the Rue du Nouveau Monde is a street that is often flooded by overflow of the sewage system. The relief lines are parallel to the street, which means that the flow is transversal to this street. So as the runoff doesn't flow from the top to the bottom of the street, but crosses the street, it means that the solutions that can be implemented has to be on a specific side of the street in order to avoid the runoff on this street. Indeed, if the runoff is caught before reaching the street, it really decreases the possible runoff. Moreover, if we can catch this runoff, we can avoid that this runoff enters the sewage system. So, the most relevant solutions are the filter strips and infiltration trenches. It is important to determine the volume needed depending on the desired effect.



Figure 4.20: Catchment of the rue du Nouveau Monde (in violet). [QGIS]

An important issue of this modeling is to take into account the combined sewage system. The values of the wastewater each house produces is not known, I will only consider that there is rainwater in the sewage system, as I work with heavy rain, so the discharge of wastewater is negligible. So, it is significant to be critical about the interpretation of this result and keep in mind that it's not exactly the representation of the reality but a study in order to see which solutions can give the most reduction of flow.

The modeling of the Rue du Nouveau Monde requires several steps :

- Simplified model : The first model only considers the catchments for each outfall. As the Rue du Nouveau Monde has more than one exit of water, it is necessary to determine several catchments. There are exactly seven outfalls, so seven catchments. The seven catchments are determined according the sewage system bringing water to the corresponding outfall. The different catchments have a surface area between 0.42 ha and 15.7 ha. The global slope is roughly constant and equals 3.75 %. As all the catchment have

the same land cover, they all have the same percentage of imperviousness, depression storage and Manning coefficient. The Rue du Nouveau monde is a street surrounded by a residential district. These plots of house have a square shape, and the surface area of a lot is around 300 m^2.

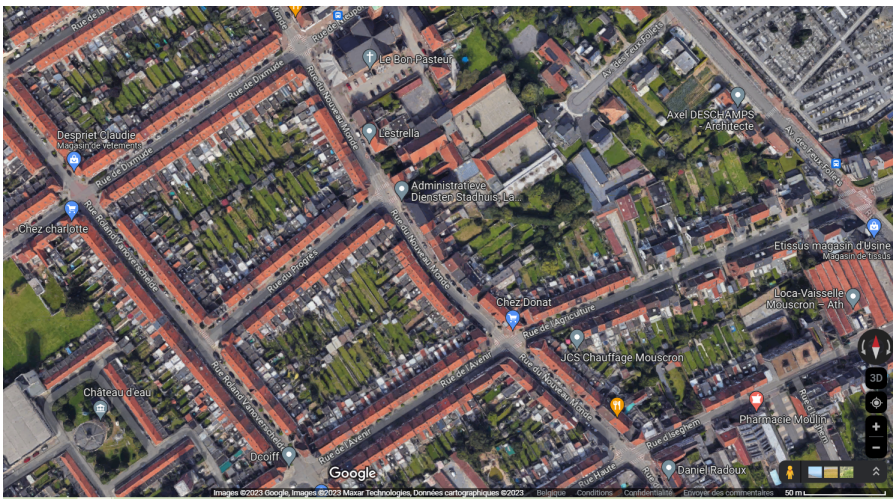


Figure 4.21: Rue du Nouveau Monde. [Google Maps]



Figure 4.22: Rue du Nouveau Monde. [Google Maps]

According to appendix B.1, when the area of a lot is less than 500 m^2, the percentage of imperviousness is 65 %. For the runoff curve number, the soil is loamy, that corresponds to the soil group A and gives a value of 77, so the default value 80 is used by facility. The value of the depression storage and Manning coefficient come from appendix D.1. The depression storage of impervious surface equals 1 mm, and for pervious surfaces 5 mm for lawn. The Manning coefficient for impervious surfaces corresponds to the one of

asphalt 0.012 and for pervious surfaces to the lawn 0.1. This first step allows us to understand how the catchments are spread.

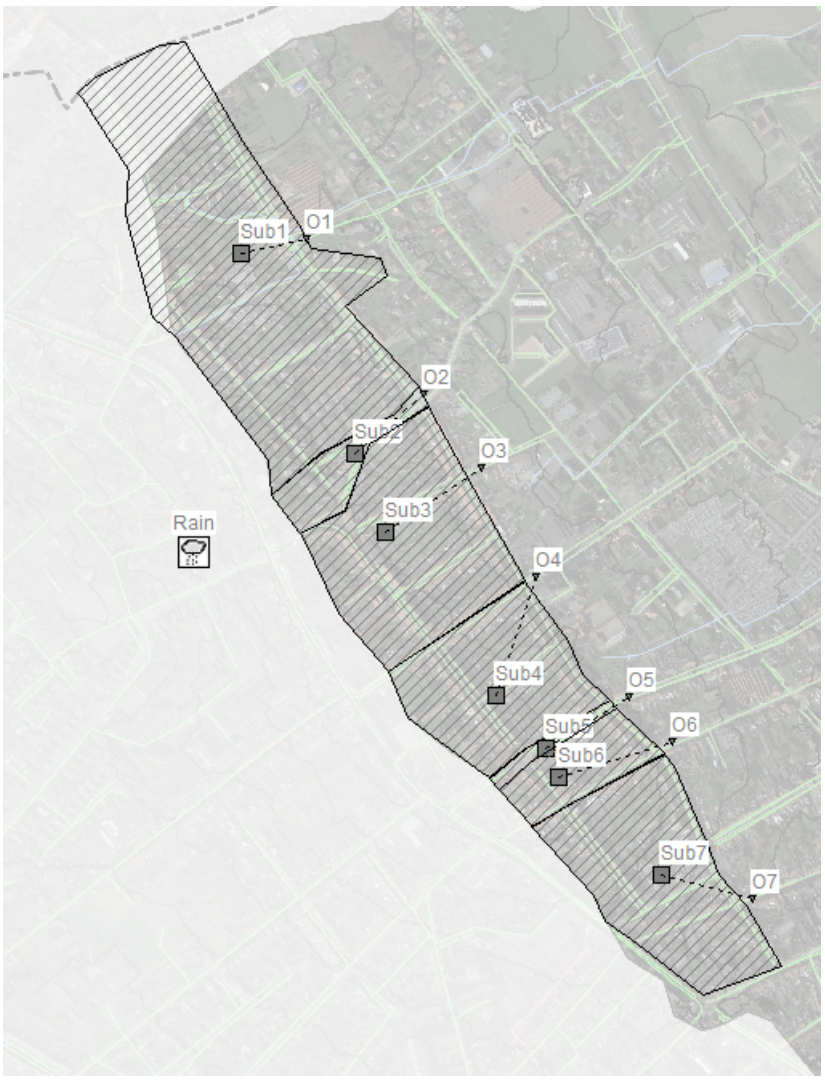


Figure 4.23: Preliminary model. [EPA SWMM]

- Discretized model : In this model, the land cover are more precisely determined, they are grouped into three categories : impervious surfaces (roads and houses), lawn areas, residential areas. For the entire model, the number of subcatchments reaches 64. Each subcatchment accounts between 2 and 17 subcatchments with a surface between 0.18 ha and 1.83 ha. The characteristics of the three land uses :

	Impervious	Lawn	Residential
% imperviousness	100	40	65
d-storage impervious [mm]	0.5	0.05	1
d-storage pervious [mm]	/	5	5
n impervious	0.025	0.01	0.012
n pervious	/	0.1	0.1

Table 4.7: Parameters of the subcatchments. [21]

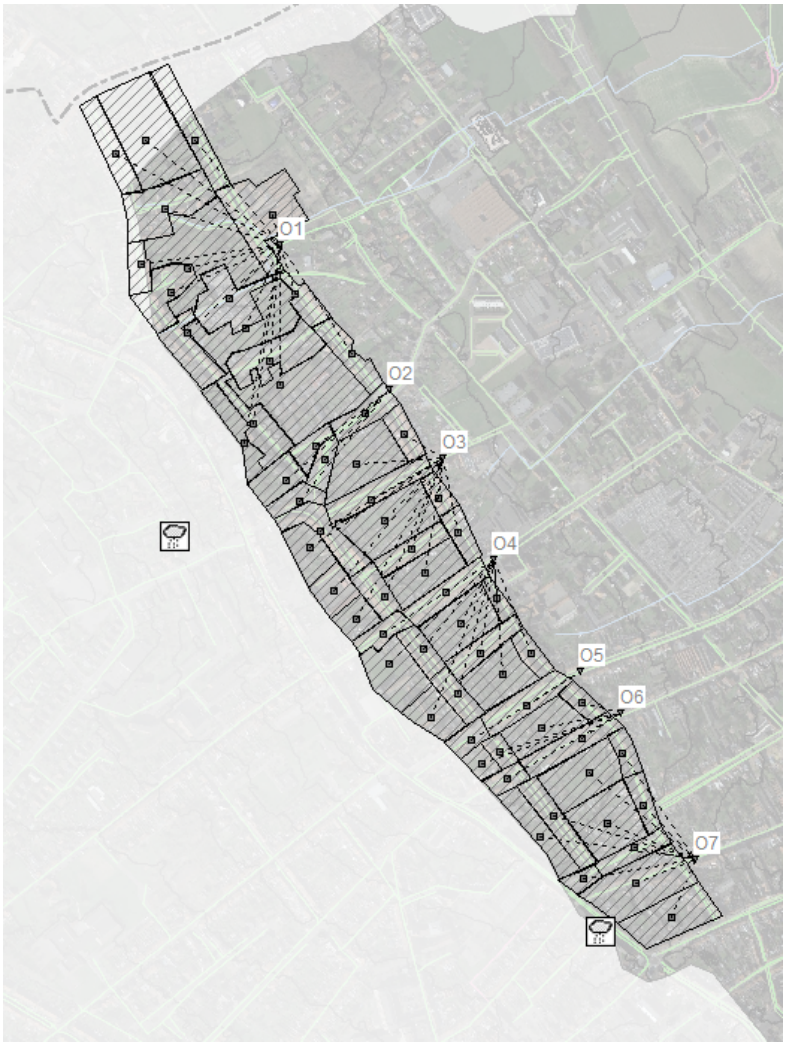


Figure 4.24: Discretized model. [EPA SWMM]



Figure 4.25: Zoom on the discretized model. [EPA SWMM]

- Sewage system : All the sewage system is added and the subcatchments are connected to the drainage system. All the conduits have a circular shape with diameters from 0.3 m to 0.7 m. These diameters are extracted from Q-GIS information. The Manning coefficient of the conduit is 0.01.



Figure 4.26: Drainage system. [EPA SWMM]

- Filter strips : The previous model represents the present drainage system. The mitigation studied here is the filter strip. These filter strips are subcatchments with an impervious percentage 0, a depression storage for pervious surfaces 7.5 mm and a Manning coefficient for pervious surfaces 0.24. The last parameter is the rain gage that has a rain of intensity and duration null. The filter strips studied have a flow path of 0.5 m and 1 m, are situated along the streets.

- Infiltration trenches : The infiltration trenches are subcatchments with an impervious percentage 0, a depression storage for pervious surfaces 360 mm and a Manning coefficient for pervious surfaces 0.24. The rain gage gives also a null rain as for the filter strips. They are also situated along the streets but here, their width is 0.5 m and 1m.



Figure 4.27: Filter strips and infiltration trenches. [EPA SWMM]

- Zoom model : In order to see the impact of a localized solution, a zoom is done on a residential district. The discretization is even more precised. The differentiation between roof and roads is done. The district is a square surrounded by roads. The houses are along the road and have a garden towards the interior of the plot. This means that the whole road is lined with houses. The flow path is assumed to go from bottom to top through a drain to the downstream sewage system, and does not stop to houses.



Figure 4.28: Runoff through the plot of houses. [Google Maps]

Here the different land covers :

	Roads	Lawn	Steep roof	Flat roof
% impreviousness	100	40	100	100
slope [%]	3.75	3.75	30	0.01
d-storage impervious [mm]	1	0.05	0	20
d-storage pervious [mm]	/	5	/	/
n impervious	0.033	0.01	0.017	0.05
n pervious	/	0.1	/	/

Table 4.8: Parameters of the subcatchments.[21]

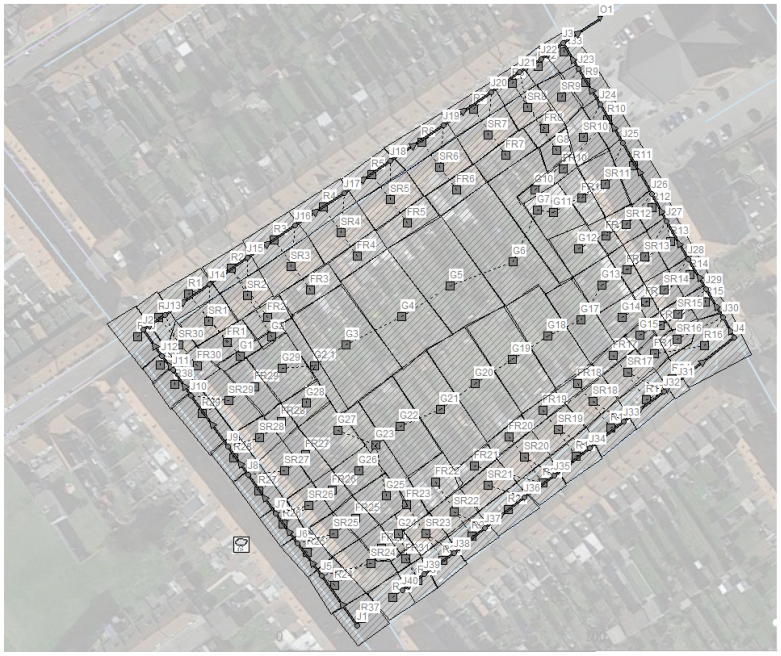


Figure 4.29: Zoom on a district. [EPA SWMM]

- Green roof : the solution analyzed here is the replacement of pitched roofs by vegetated flat roofs. The two proportions used are 20% and 100% flat roofs for the whole neighbourhood. The steep roofs are just transformed into flat roofs that have more storage.

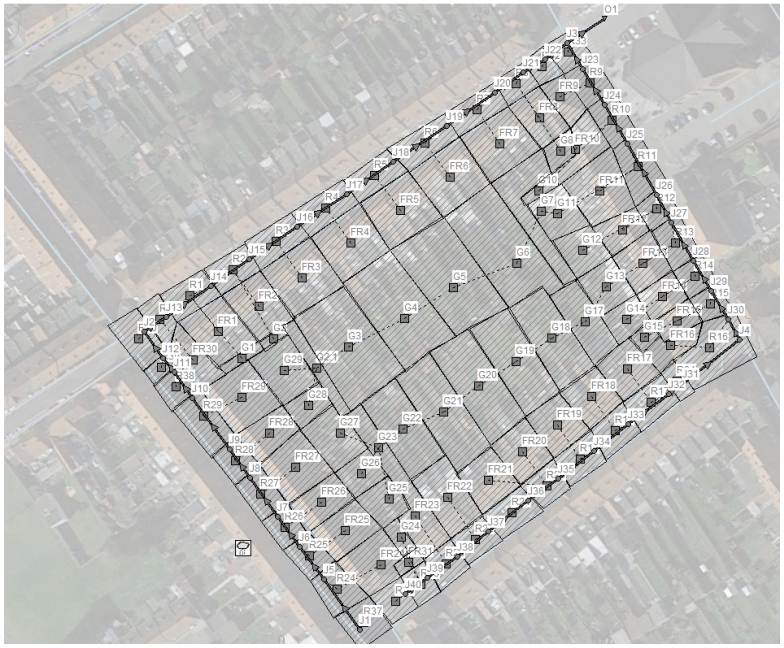


Figure 4.30: Green roof 100%. [EPA SWMM]

The different outcomes that are useful to compare are the average and maximum flow, and the total volume at each outfall. It is also relevant to check the evolution in time of the total inflow.

Here are the different graphs about the average flow with different duration of rain and different return periods for the model discretized and with the LID solutions :

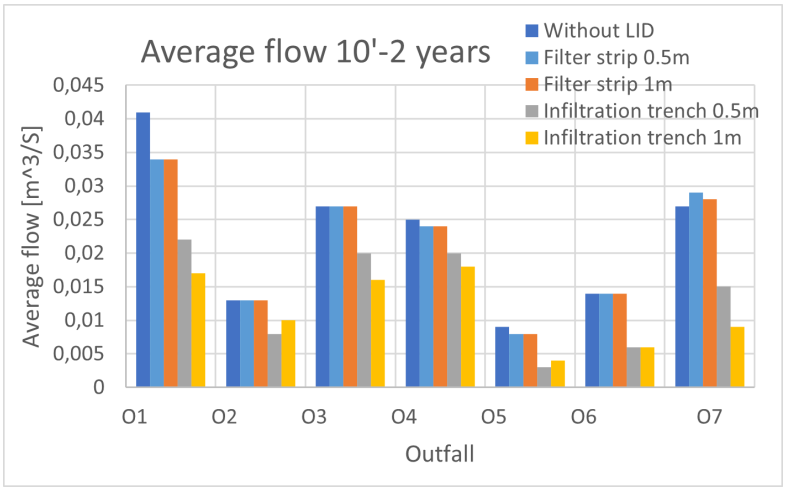


Figure 4.31: Average flow for t_r = 10' and T_r = 2 years.

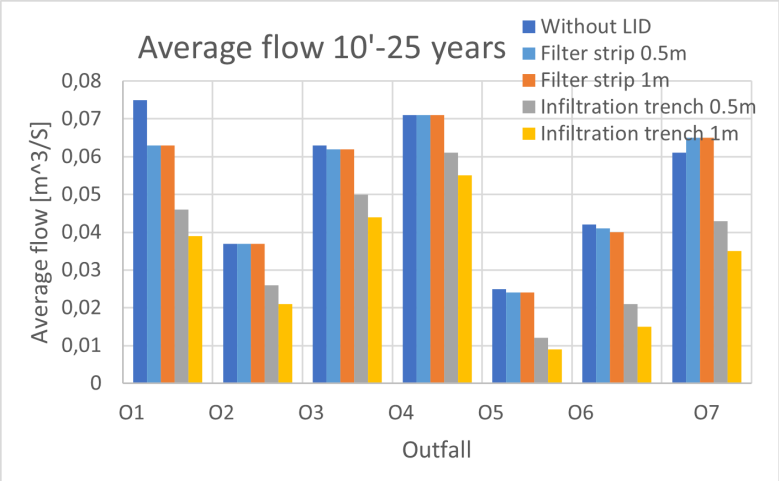


Figure 4.32: Average flow for t_r = 10' and T_r = 25 years.

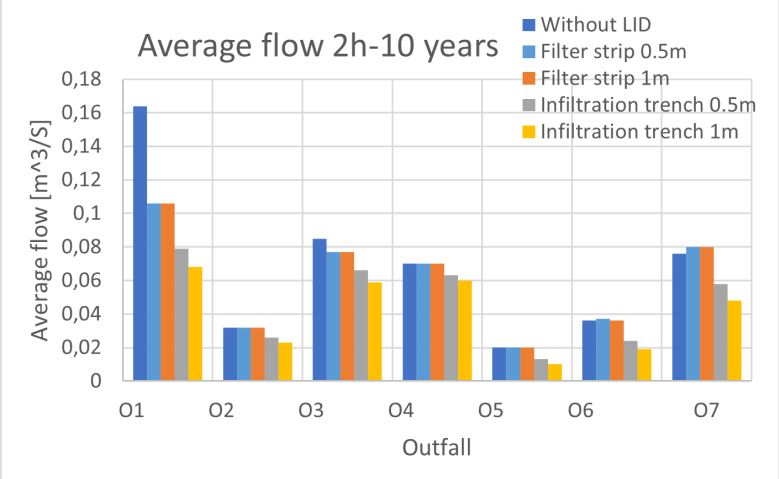


Figure 4.33: Average flow for t_r = 2h and T_r = 10 years.

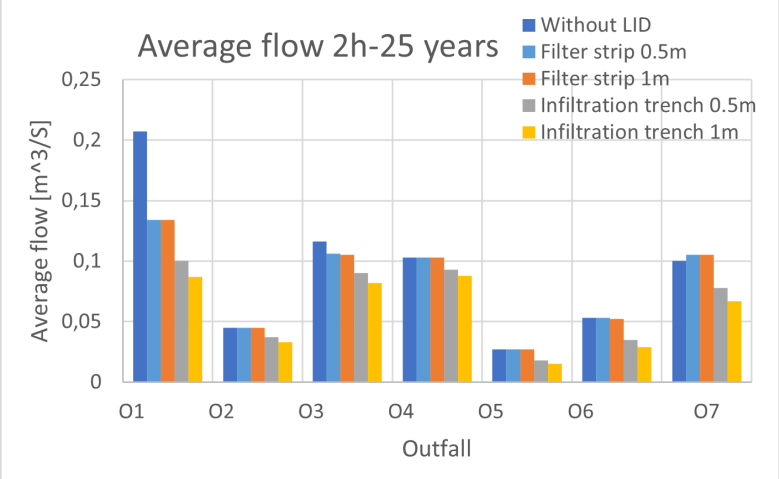


Figure 4.34: Average flow for t_r = 2h and T_r = 25 years.

We can see on the graph the different effects of the filter strips and infiltration trenches. We can clearly see that infiltration trenches have a positive impact on the average flow. Depending on the outfall observed, the reduction of flow can reach 66 % for the infiltration trench of 0.5m and 1m, for the rain with a duration of 10 minutes and a return period of 2 years. For the rain with the same duration but a return period of 25 years, the reduction reaches 50 % for the trench of 0.5m, and 64 % for the one of 1m. For the rain with a duration of 2h, the proportion of diminution is the same for the two return periods, about 50 % for 0.5m and 58 % for 1m trenches. This shows that infiltration trenches are really efficient for short and long rainfall to decrease the average flow. Moreover, the infiltration trenches with a width of 1m are more efficient than these with 0.5m width.

About the filter strips, they have the same effect with different width. Indeed, it is due to the flow paths that have the same length, it is the area that is bigger. We can clearly see that the filter strips has lower impact than the infiltration trenches, but the diminution still reaches 27 % and 46 % for the outfall 1 on respectively short and long rain. But it is not the tendency for all the outfall. In general the filter strips have a minimum influence on the flow going out the catchments, sometimes it even upper the average outflow.

Here are the different graphs about the maximum flow with different duration of rain and different return periods for the model discretized and with the LID solutions :

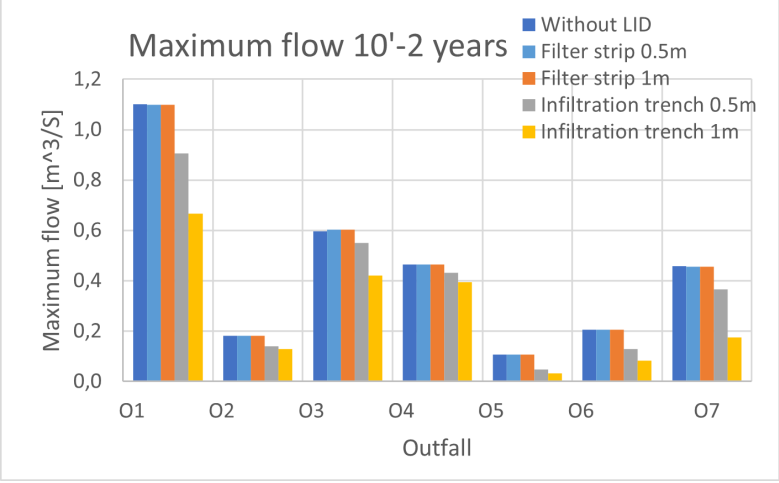


Figure 4.35: Maximum flow for $t_r = 10$' and $T_r = 2$ years.

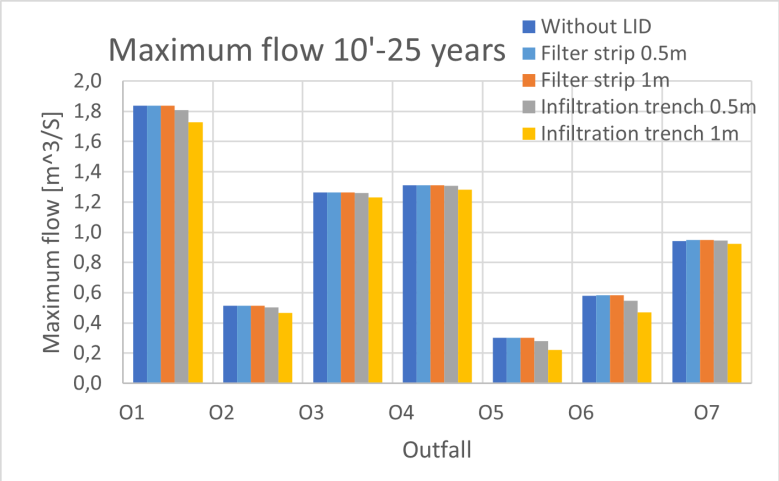


Figure 4.36: Maximum flow for t_r = 10' and T_r = 25 years.

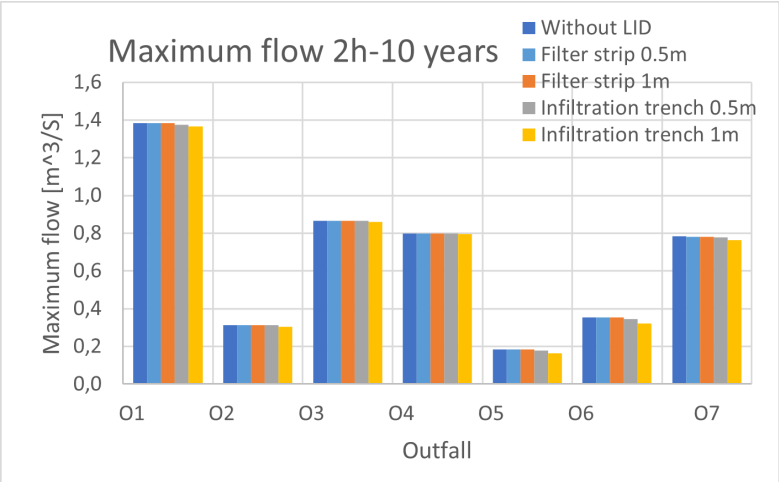


Figure 4.37: Maximum flow for t_r = 2h and T_r = 10 years.

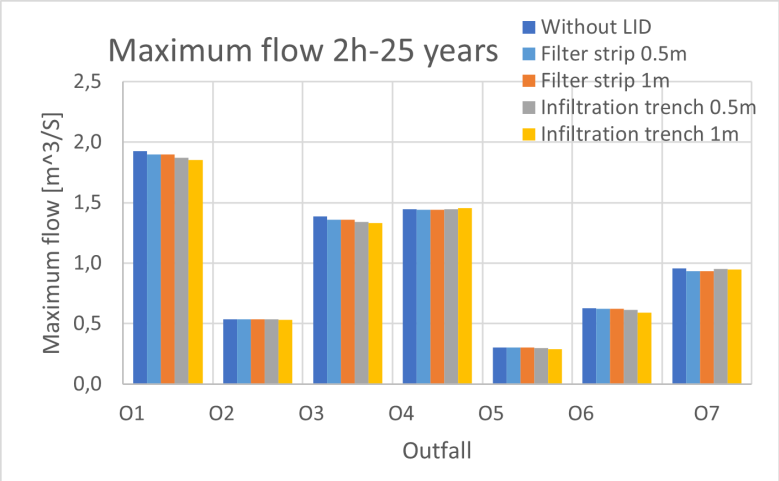


Figure 4.38: Maximum flow for t_r = 2h and T_r = 25 years.

On these graphs, it is interesting to focus on the evolution of the decrease in function of the different rains. Indeed, even if only the LID that has an impact is the filter strip, its beneficial effect decreases a lot with the increase of the return period and the duration of the rain. For the first type of rain the decreased reaches 61 % but for the longest return period it drops to 2 %. It really shows that these LID are useful for short rains with lower intensities for a decreased in the maximum flow.

Here are the different graphs about the total volume with different duration of rain and different return periods for the model discretized and with the LID solutions :

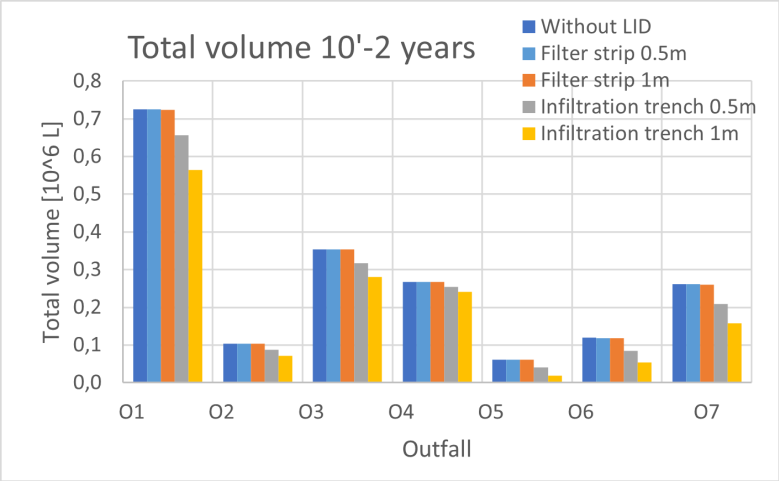


Figure 4.39: Total volume for t_r = 10' and T_r = 2 years.

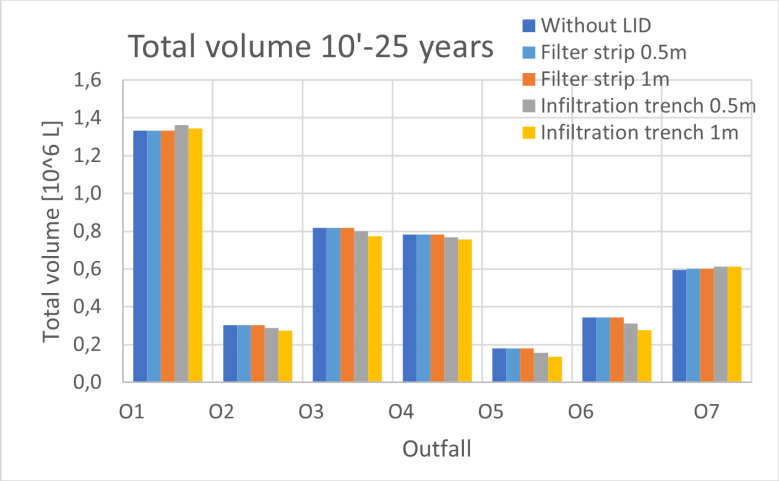


Figure 4.40: Total volume for t_r = 10' and T_r = 25 years.

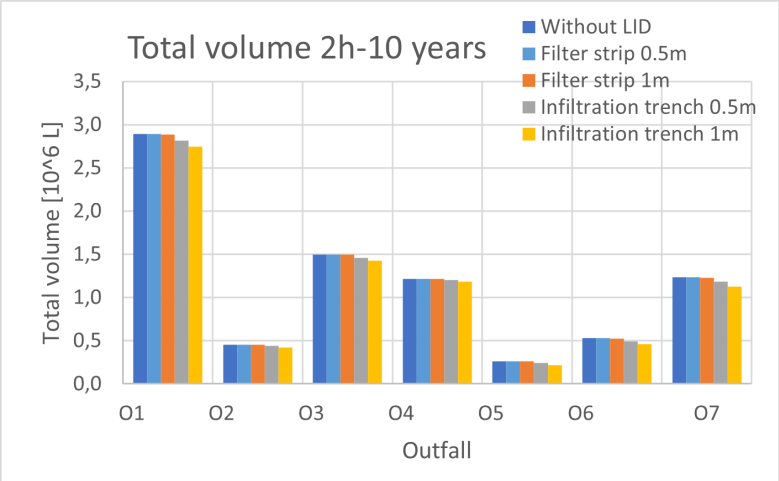


Figure 4.41: Total volume for $t_r = 2$h and $T_r = 10$ years.

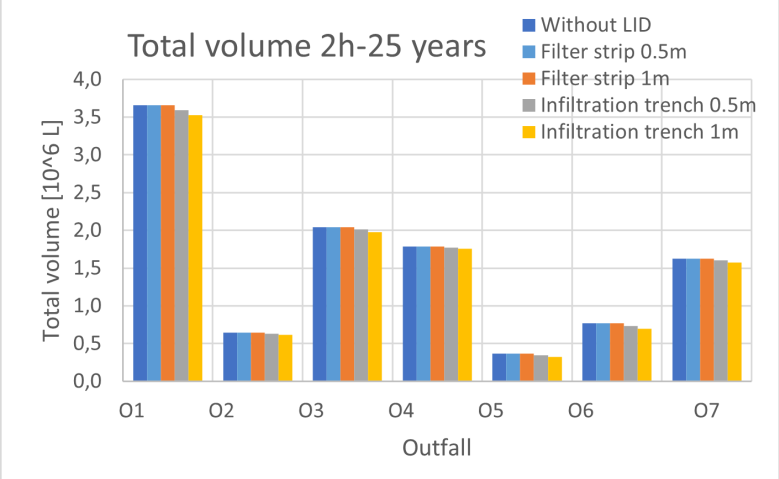


Figure 4.42: Total volume for $t_r = 2$h and $T_r = 25$ years.

It is obvious to make a parallelism between the graphs of the total volume and the preceding graphs about the maximum flow. The conclusions are really similar. That means that the longer and the stronger is the rain, the less efficient is the infiltration trench. Moreover, the filter strips have nearly no effect.

Here are the different evolutions in time of the total inflow with different duration of rain and different return periods for the model discretized and with the LID solutions :

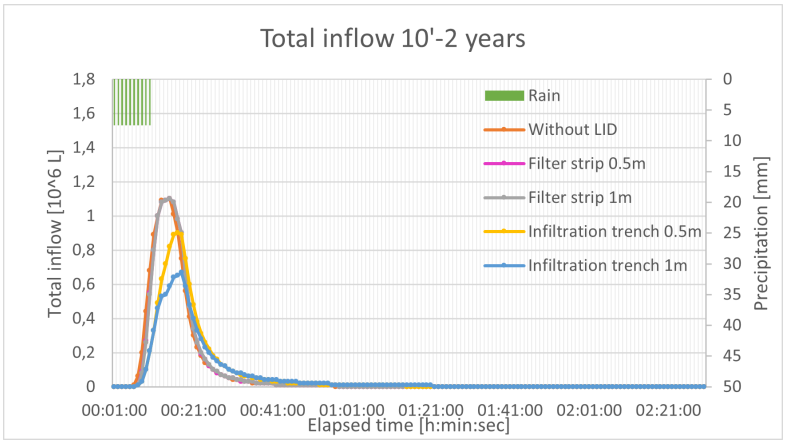


Figure 4.43: Total inflow for $t_r = 10$' and $T_r = 2$ years.

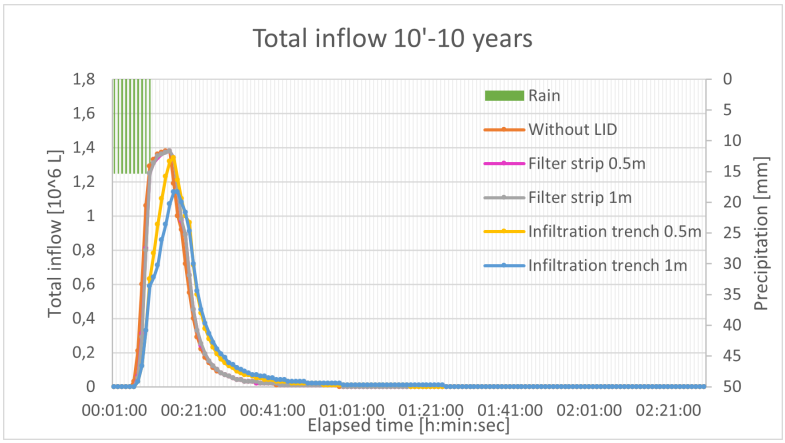


Figure 4.44: Total inflow for $t_r = 10$' and $T_r = 10$ years.

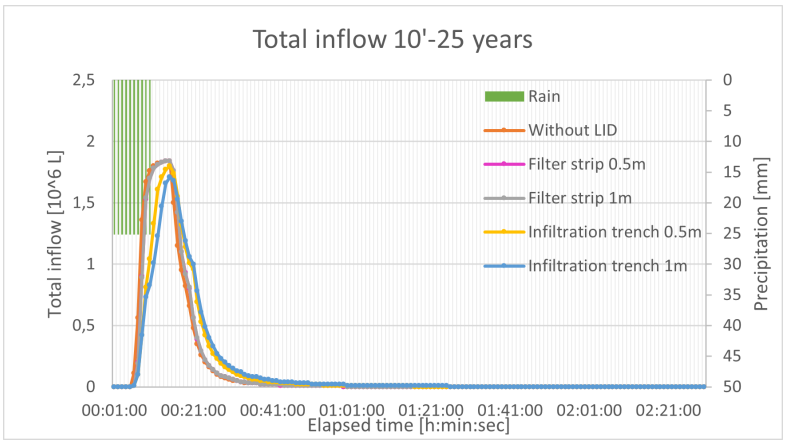


Figure 4.45: Total inflow for $t_r = 10$' and $T_r = 25$ years.

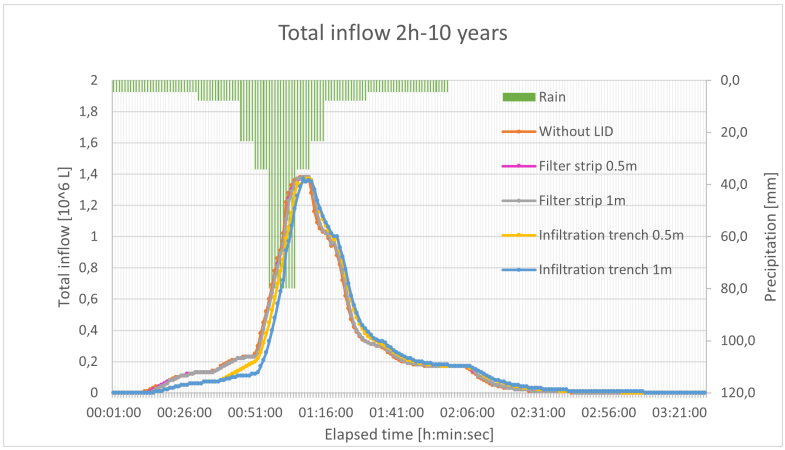


Figure 4.46: Total volume for $t_r = 2$h and $T_r = 10$ years.

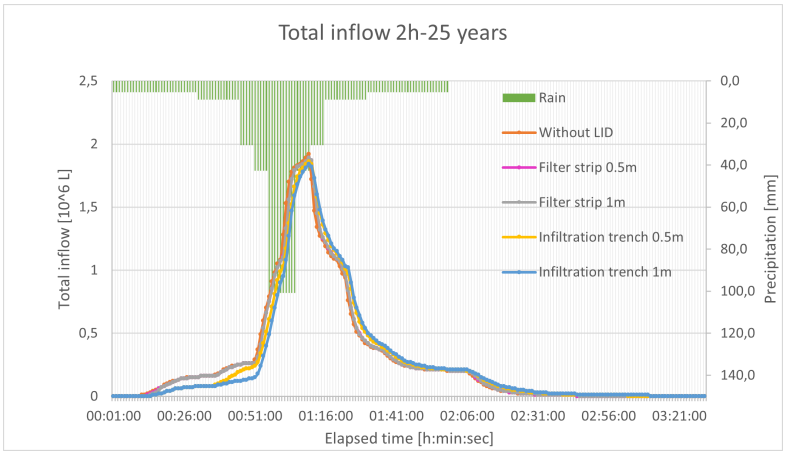


Figure 4.47: Total volume for $t_r = 2$h and $T_r = 25$ years.

The evolution in time of the total inflows shows two different important characteristics. The first one is the delay of the discharge peak compared to the rain. This delay is normal and due to the time of concentration of the catchment. The second characteristic is the delay and the diminution of the peak inflow with the infiltration trenches compared to the normal sewage for short rain. This result is expected because the infiltration trenches are excavations that store the water. The volume storage and flow path imply that these trenches need time to be completely wet and to create runoff. Indeed, the flow path of these trenches is really long, this means that the water has a lot of time to infiltrate into the soil and to reach the outlet, that gives a delay in time. This diminution and delay lowers with the return period of the rain. For a long event of rain, these two beneficial points are really decreased, that means that the infiltration trenches are specifically efficient for short rain with small return period. Concerning the filter strips, these LID controls are only useful for the pollutants removing, and not for reducing the

peak discharge. In order to treat a peak discharge and particles pollutants it can be wise to use these two LID controls together.

The last flood mitigation for this street is the integration of green roof. Here are graphs about the average and maximum flow and the total volume :

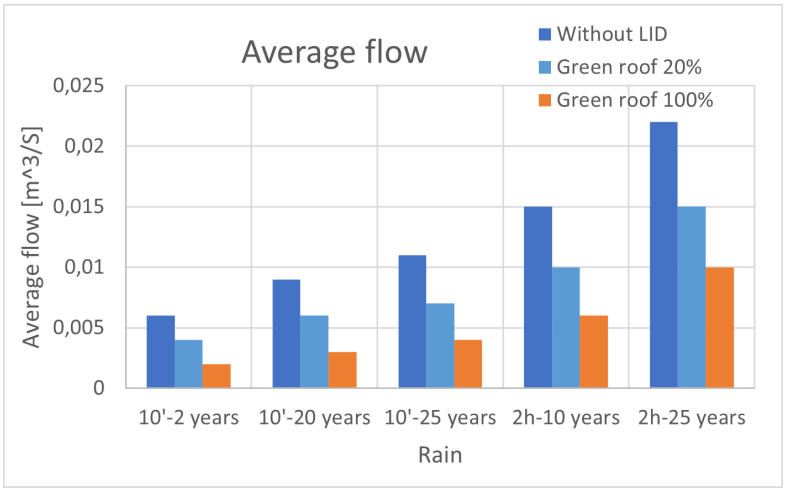


Figure 4.48: Average flow for different durations and return periods of rain.

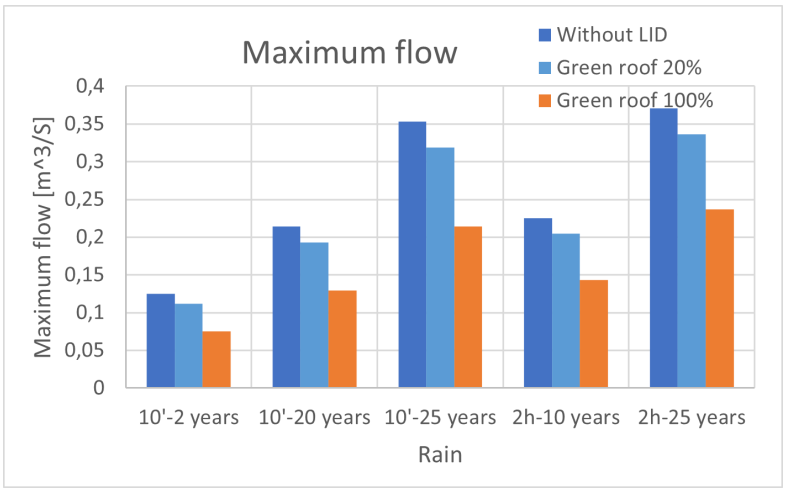


Figure 4.49: Maximum flow for different durations and return periods of rain.

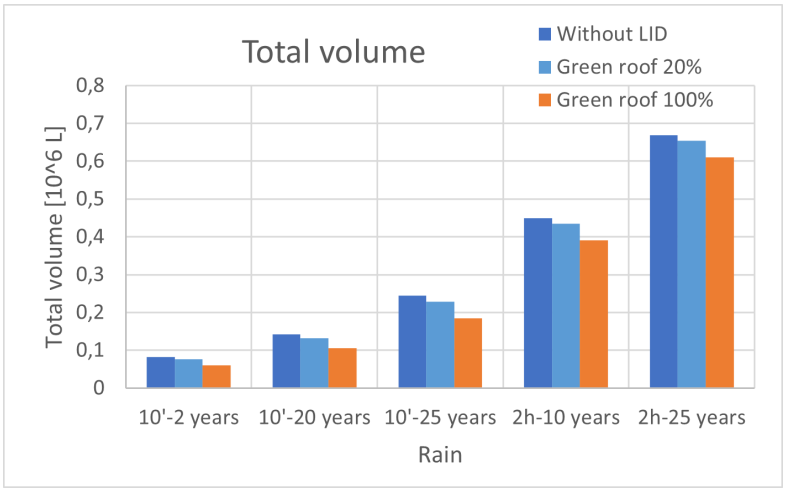


Figure 4.50: Total volume for different durations and return periods of rain.

The average flow decreases in a constant way not depending on the differents type of rain. The reduction is approximately 32% and 55% for respectively 20% of green roof and 100% of green roof. The same tendency is observed for the maximum flow and total volume. The maximum flow is decreased at 10 % and 40 % while the total volume has a smaller reduction 2% and 8% for 20% and 100% of green roofs. This shows that the implementation of green roofs in urban area is a solution that has a beneficial impact on both the outcomes.

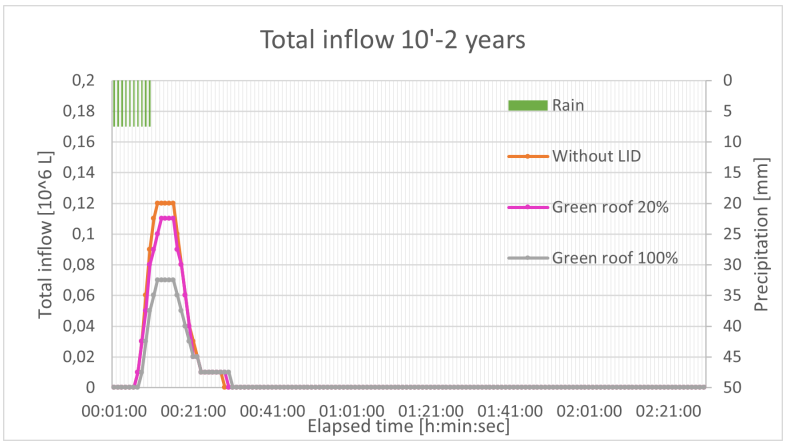


Figure 4.51: Total inflow for t_r = 10' and T_r = 2 years.

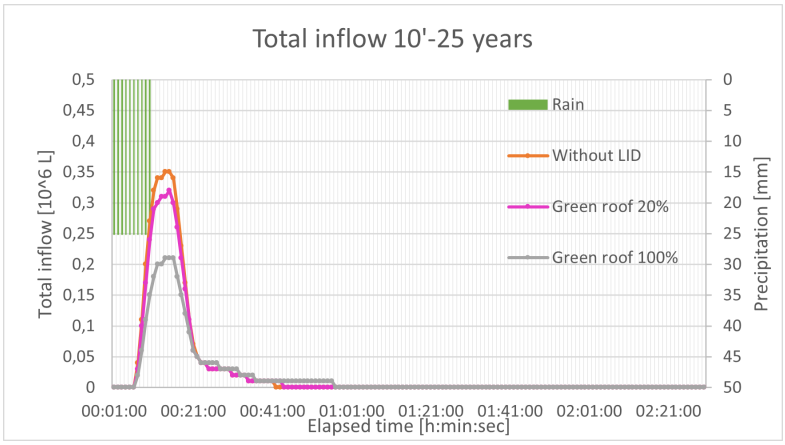


Figure 4.52: Total inflow for t_r = 10' and T_r = 25 years.

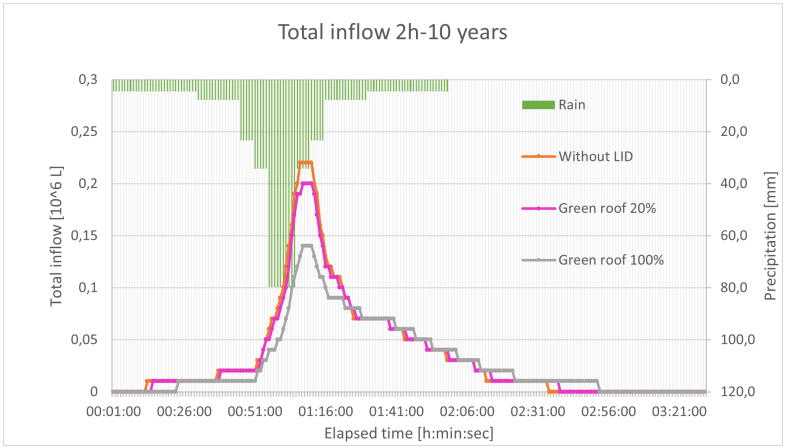


Figure 4.53: Total inflow for t_r = 2h and T_r = 10 years.

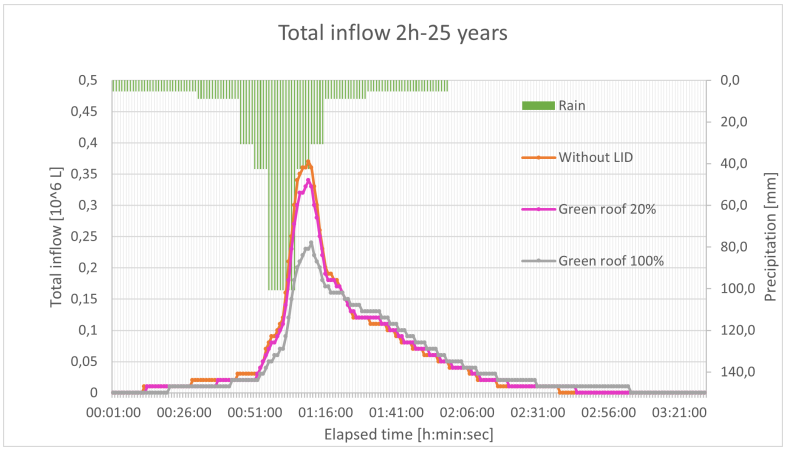


Figure 4.54: Total inflow for t_r = 2h and T_r = 25 years.

The evolution of the total inflow has a really similar trend regardless of the situation. The only parameter that differentiates the curves is the intensity of the

total inflow. Looking more precisely, the green roof implies a very small delay in the inflow peak. This solution of green roof is really efficient no matter which type of rain falls.

To conclude about the Rue du Nouveau Monde, the most efficient solution is the replacement of steep roof by green roof. Unfortunately, this solution can only be implemented for new residential districts and is not on the public domain. It is a solution that is at the discretion of each municipality in the planning permit. The floods mitigations that can be implemented on public domain and that has a limited efficiency for long rain but a good efficiency in a short and low rain is the infiltration trench. They delay and reduce the inflow peak. They can be constructed even if the road is already built.

4.4.2 Ferme de la Blommerie

This location has a particular situation. Indeed, the place that was flooded before the implementation of the check valve, was flooded by a drainage system that was supposed to carry only waste water. However, the rainwater coming from a downstream pipe went back to the waste water conduit that lead to overflow due to a pressurized conduit.



Figure 4.55: Catchment of the Ferme de la Blommerie (in red). [QGIS]

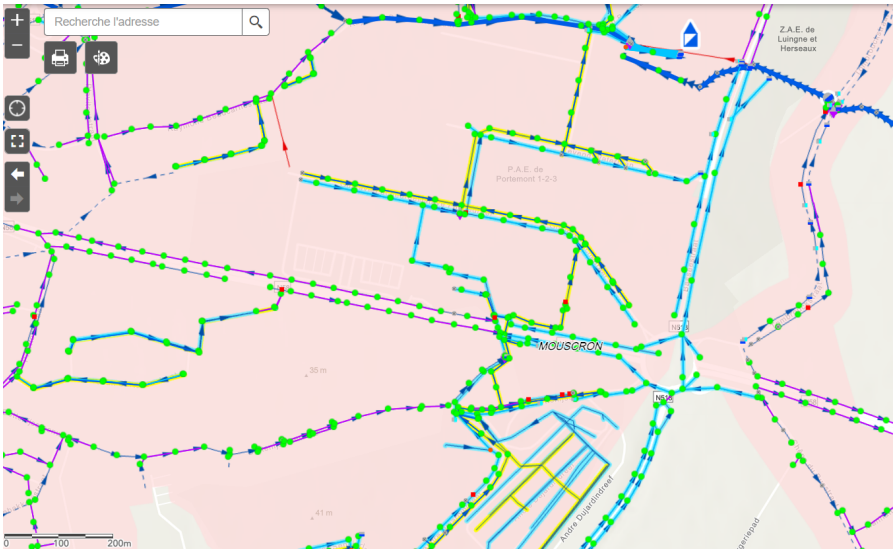


Figure 4.56: Drainage system with rain water (in blue) and wastewater (in yellow). [9]

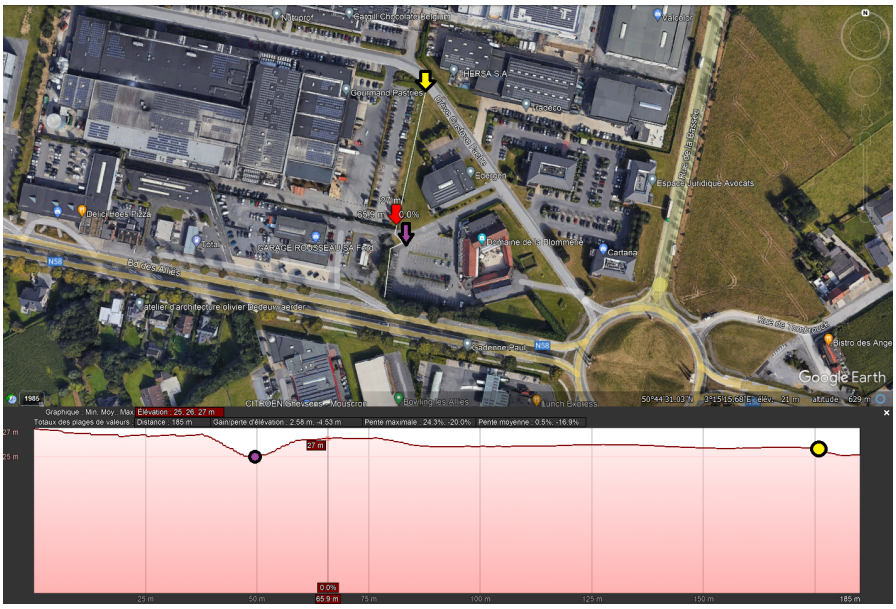


Figure 4.57: Topography of the Ferme de la Blommerie. [Google Maps]

So, in order to see which mitigation can be helpful, we will look at the runoff going through the conduit transporting the rain water. The design will not include sewage system. So, the first model consists of different subcatchments with different properties where the rain can infiltrate and runoff until the outfall that is the entry of the rainwater in the pipe described above. The second model includes a mitigation solution : a filter strip and infiltration trench.

- Model 1 : The catchment, that has a surface area of 0.74 km^2, is discretized

into 21 subcatchments that are categorized according to the land use. Here are the different parameters of the subcatchments :

	Culture	Industrial	Residential	Road
% impreviousness	40	75	30	100
d-storage impervious [mm]	0.05	0.05	0.5	0.5
d-storage pervious [mm]	4	2	0.05	/
n impervious	0.06	0.012	0.025	0.025
n pervious	0.1	0.1	0.1	/

Table 4.9: Parameters of the subcatchments.



Figure 4.58: Model 1. [EPA SWMM]

- Model 2 : The second model includes mitigation solutions, the two floods mitigations are filter strip and infiltration trench. The LIDs are implemented on the roundabout through each the runoff passes by. The filter strip and infiltration trench have the same characteristics as explained in the section 4.4.1 at page 73. The surface of these LIDs is 0.012 ha with a flow path or width of 0.5m.



Figure 4.59: Model 2. [EPA SWMM]

Since the modeling doesn't include a sewage system, the only outcome that is interesting to compare, is the evolution in time of the total inflow :

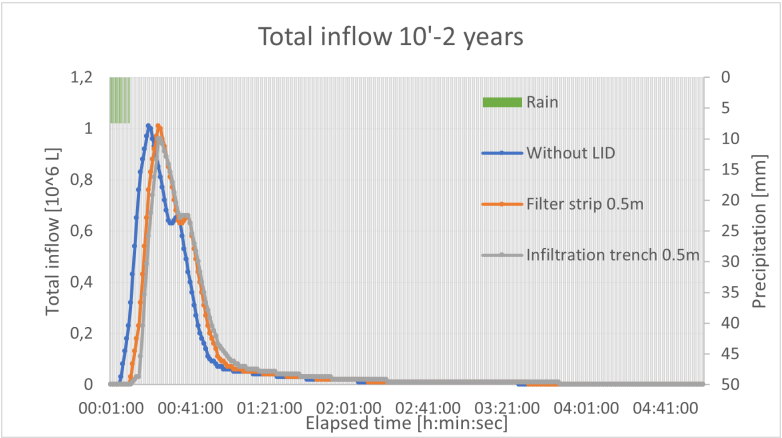


Figure 4.60: Total inflow for $t_r = 10$' and $T_r = 2$ years.

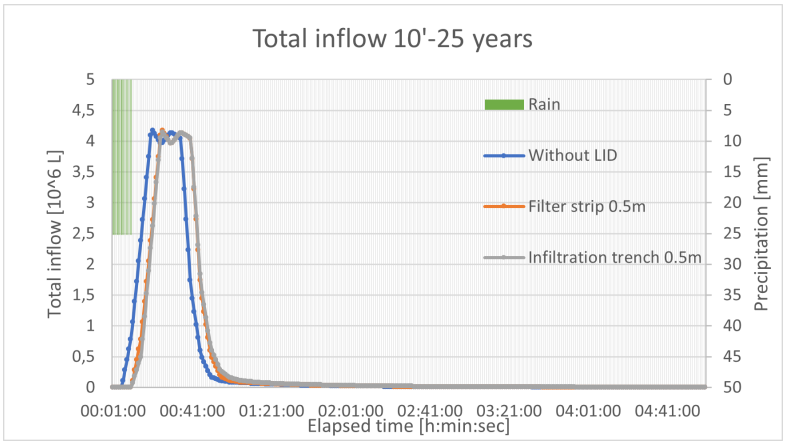


Figure 4.61: Total inflow for t_r = 10' and T_r = 25 years.

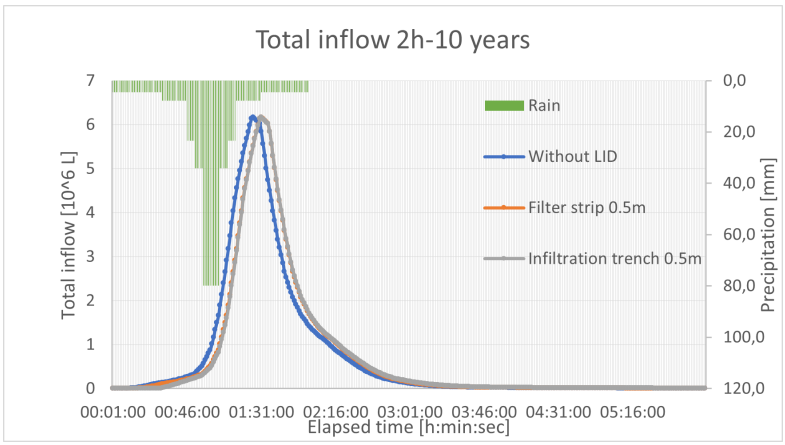


Figure 4.62: Total inflow for t_r = 2h and T_r = 10 years.

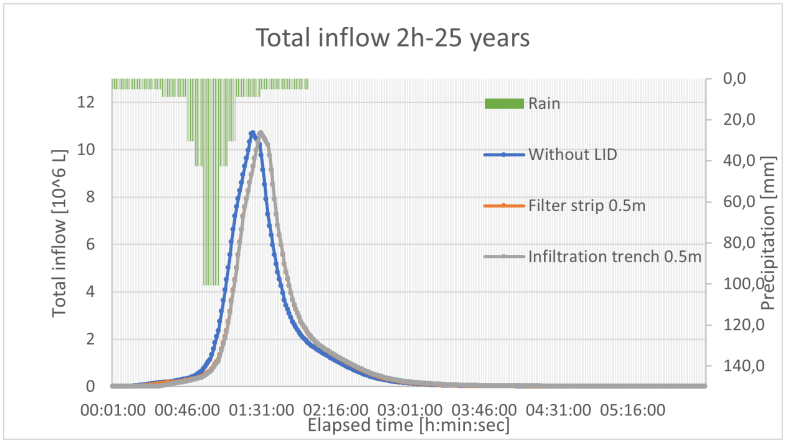


Figure 4.63: Total inflow for t_r = 2h and T_r = 2 years.

The two LIDs solutions induce a delay of approximately 5 min compared to the normal situations. Unfortunately, there isn't any reduction of the peak inflow.

These mitigations are not efficient for our problem. This means that another solution have to be investigated.

A last solution is to implement a reservoir at the same place than the filter strip and infiltration trench. This reservoir would store the water and avoid such a big inflow at the outlet. According to Groupe de travail "bassins d'orage" du GTI [2], we can calculate the necessary volume of retention V_s depending on the characteristics of the rain and the subcatchments, :

$$V_s = \frac{t_r \times (Q_{in} - Q_{out})}{1000}[m^3] \tag{4.8}$$

with the incoming discharge Q_{in} :

$$Q_{in} = \frac{i_m}{10000} \sum_{j=1}^{N} C_j A_j [l/s] \tag{4.9}$$

and the outgoing discharge Q_{out} :

$$Q_{out} = \frac{Q_a \times A}{10000}[l/s] \tag{4.10}$$

with the duration of the rain t_r in [s], the mean intensity of the rain in [l/s/ha], the area A, A_j in $[m^2]$, and the discharge rate allowed by the competent authorities $Q_a = 5$ [l/s/ha].

For the two different types of rain with a return period of 10 years, we can now find the storage volume.

	t_r [s]	i_m [l/s/ha]	Q_{in} [l/s]	Q_{out} [l/s]	V_s [mˆ3]
10'	600	42.6	1865	31.52	1100
2h	7200	43.4	1900	32.12	13448

Table 4.10: Retention volume.

This means that for a rain of 10 minutes, the retention reservoir needed is of 1100 m^3, could be a reservoir of 5m depth and a radius of 7m. For a 2 hours long rain, the reservoir volume is 13448 m^3, that means 10m depth with a radius of 20m.

Conclusion

This final work is part of the research work of Thais Delfortrie in the Department of Architecture of the Ecole Polytechnique de Louvain. It consists in the SWMM modeling part of the solutions reflected during his PhD. The purpose of this brief was to find solutions to mitigate runoff to avoid sewer overflow and flooding in urban areas.

This paper began with a first chapter presenting the historical and geographical context of floods in the world. The floods are scourges that are increasingly frequent. In addition, floods do a lot of damage, so it is important to find solutions to mitigate their consequences. Then, with regard to water resources, it appears that water is a limited resource and that it is important to find solutions to spread water and therefore to store rainwater for reuse. In this first chapter, the last part focuses on events and context in Belgium.

Next, the second chapter is devoted to the water cycle and the involvement of urban areas in changing the water cycle. Because of the urbanization of our lands, the water cycle has been disrupted. The water no longer can infiltrate as much as on a natural site without urbanization, which causes runoff. In the second section of this chapter, the functioning of the hydrological model is presented as well as various examples. Finally, because of the choice of SWMM software, some studies that have been done are presented as well as their potential contribution for this study.

The third chapter presents the software SWMM, its functioning and the representation of a catchment in this software. It is a semi-distributed model that allows to represent urban catchment and their process of flow between the different compartments. SWMM is useful for the urban area since we can represent sewage system, runoff, infiltration.

The last chapter focuses on the study of the Espierres watershed. This watershed is situated in Mouscron, in Belgium. Two different places are studied in particularly : Rue du Nouveau Monde and Ferme de la Blommerie. They respectively have an overflow of the sewage system due to heavy rain and an overflow of a wastewater system due to back up water coming from a rain system. The specific steps to model such site are explored. It is really important to first determine the watershed and so on the subcatchment according to the topography and the sewage system. The subcatchments are defined according to the land uses, it is important to well calibrate all the parameters. Then, the sewage system can be added. The last step is to run a simulation. Depending on the situation we want to study, the intensity and the return period of the rain gives diverse types of rain, and so distinct effects on the simulation. With this simulation, it is possible to do some others to try to improve the situation, with some flood mitigation such as infiltration trenches, green roofs, reservoirs. The end of the chapter describes the solutions and the outcomes of these solutions.
About the Rue du Nouveau Monde, two different scales are studied. One at the scale of the catchment and the other one zoomed on a lot of houses with more detailed discretization of the subcatchments. For the study on the whole watershed, two different solutions are proposed : filter strips and infiltration trenches. These two LIDs are situated next streets. They have a width and flow path of 0.5m or 1m. The filter strip has nearly no effect on this subcatchment. It was expected because they are there to filtrate pollutants. The infiltration trenches are efficient especially for short rain with a small return period. The inflow peak is decreased and is a little bit delayed. About the more discretized solution, one mitigation proposed is the change of steep roofs by flat green roofs that allow the storage of water. The retention of the water is really valuable. It increases with the number of flat green roofs. This solution seems to be the most beneficial for this site. It shows here the importance of different scale discretization in order to study different propositions.
About the Ferme de la Blommerie, this site is modeled without the sewage system, the only outcome evaluated is the inflow at the outlet of the catchment. The two first mitigation studied are infiltration trenches and filter strips at the end of the catchment. This model shows that these two LIDs don't have any effect in term of peak inflow reduction. It is due to the total inflow coming to these systems. Indeed, the volume is way bigger than the one for the Rue du Nouveau Monde. Here we can highlight the context of the watershed. Depending on the situation, total runoff, discharge arriving to mitigation solution, they don't have the same impact. These solutions have to be chosen wisely depending on the context. The solution that should be more efficient here is a retention reservoir. This reservoir

is relevant because a huge amount of water arrives at this outlet.

This thesis point out the importance of the context in hydrological studies. In the future, these studies will become increasingly important for a smarter implementation of drainage system and use of water in urban areas.

Appendix A: Cross section for conduits

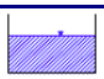
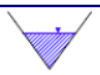
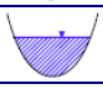
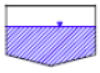
Name	Parameters	Shape	Name	Parameters	Shape
Circular	Full Height		Circular Force Main	Full Height, Roughness	
Filled Circular	Full Height, Filled Depth		Rectangular - Closed	Full Height, Width	
Rectangular – Open	Full Height, Width		Trapezoidal	Full Height, Base Width, Side Slopes	
Triangular	Full Height, Top Width		Horizontal Ellipse	Full Height, Max. Width	
Vertical Ellipse	Full Height, Max. Width		Arch	Full Height, Max. Width	
Parabolic	Full Height, Top Width		Power	Full Height, Top Width, Exponent	
Rectangular-Triangular	Full Height, Top Width, Triangle Height		Rectangular-Round	Full Height, Top Width, Bottom Radius	
Modified Baskethandle	Full Height, Bottom Width, Top Radius		Egg	Full Height	
Horseshoe	Full Height		Gothic	Full Height	
Catenary	Full Height		Semi-Elliptical	Full Height	
Baskethandle	Full Height		Semi-Circular	Full Height	
Irregular Channel	Transect Coordinates		Custom Closed Shape	Full Height, Shape Curve Coordinates	
Street or Roadway	See Section 3.3.6				

Figure A.1: Available cross section shapes for conduits. [28]

Appendix B: SCS curve numbers

Land Use Description	Hydrologic Soil Group			
	A	B	C	D
Cultivated land				
Without conservation treatment	72	81	88	91
With conservation treatment	62	71	78	81
Pasture or range land				
Poor condition	68	79	86	89
Good condition	39	61	74	80
Meadow				
Good condition	30	58	71	78
Wood or forest land				
Thin stand, poor cover, no mulch	45	66	77	83
Good cover[2]	25	55	70	77
Open spaces, lawns, parks, golf courses, cemeteries, etc.				
Good condition: grass cover on 75% or more of the area	39	61	74	80
Fair condition: grass cover on 50-75% of the area	49	69	79	84
Commercial and business areas (85% impervious)	89	92	94	95
Industrial districts (72% impervious)	81	88	91	93
Residential[3]				
Average lot size (% Impervious[4])				
1/8 ac or less (65)	77	85	90	92
1/4 ac (38)	61	75	83	87
1/3 ac (30)	57	72	81	86
1/2 ac (25)	54	70	80	85
1 ac (20)	51	68	79	84
Paved parking lots, roofs, driveways, etc.[5]	98	98	98	98
Streets and roads				
Paved with curbs and storm sewers[5]	98	98	98	98
Gravel	76	85	89	91
Dirt	72	82	87	89

Figure B.1: SCS Curve numbers. [28]

Appendix C: Runoff coefficient

Rural Land Use	Lower Bounds	Upper Bounds
Cultivated Land, Sand & Gravel Soils	0.25	0.35
Cultivated Land, Sandy Loam Soils	0.20	0.52
Cultivated Land, Clay & Silt Loam Soils	0.40	0.72
Cultivated Land, Tight Clay Soils	0.50	0.82
Pasture, Sandy Loam Soils	0.10	0.22
Pasture, Clay & Silt Loam Soils	0.30	0.42
Pasture, Tight Clay Soils	0.40	0.60
Meadow	0.10	0.50
Woodland, Sandy Loam Soils	0.10	0.30
Woodland, Clay & Silt Loam Soils	0.30	0.50
Woodland, Tight Clay Soils	0.40	0.60
Bare Rock	0.82	0.94
Desert	0.30	0.55

Figure C.1: Runoff coefficients. [19]

Urban Land Use	Lower Bounds	Upper Bounds
Parking	0.85	0.96
Commercial	0.71	0.89
Streets	0.70	0.91
Industrial	0.67	0.86
Residential Lots, High Density	0.25	0.54
Residential Lots, Medium Density	0.19	0.50
Residential Lots, Low Density	0.14	0.46
Railway Yards	0.20	0.35
Playgrounds	0.20	0.30
Sports Fields	0.20	0.35
Parks	0.10	0.25
Cemetaries	0.10	0.25

Figure C.2: Runoff coefficients. [19]

Man Made Surfaces	Lower Bounds	Upper Bounds
Roofs, Steeply Sloping	0.90	0.95
Roofs, Small Flat	0.90	0.95
Roofs, Large Flat	0.75	0.95
Asphalt	0.70	0.95
Pervious Asphalt	0.55	0.80
Concrete	0.70	0.95
Pervious Concrete	0.60	0.80
Concrete Blocks, Uncemeted Joints	0.50	0.70
Concrete Blocks, Cemeted Joints	0.70	0.85
Gravel	0.50	0.60
Earth	0.50	0.50
Grass, Poor Condition	0.32	0.62
Grass, Fair Condition	0.25	0.60
Grass, Good Condition	0.21	0.58
Turf Block	0.15	0.30

Figure C.3: Runoff coefficients. [19]

Appendix D: Manning coefficient

Surface	n
Smooth asphalt	0.011
Smooth concrete	0.012
Ordinary concrete lining	0.013
Good wood	0.014
Brick with cement mortar	0.014
Vitrified clay	0.015
Cast iron	0.015
Corrugated metal pipes	0.024
Cement rubble surface	0.024
Fallow soils (no residue)	0.05
Cultivated soils	
Residue cover < 20%	0.06
Residue cover > 20%	0.17
Range (natural)	0.13
Grass	
Short, prairie	0.15
Dense	0.24
Bermuda grass	0.41
Woods	
Light underbrush	0.40
Dense underbrush	0.80

Figure D.1: Manning coefficients for overland flow. [28]

Conduit Material	n
Asbestos-cement pipe	0.011 - 0.015
Brick	0.013 - 0.017
Cast iron pipe	
- Cement-lined & seal coated	0.011 - 0.015
Concrete (monolithic)	
- Smooth forms	0.012 - 0.014
- Rough forms	0.015 - 0.017
Concrete pipe	0.011 - 0.015
Corrugated-metal pipe	
(1/2-in. x 2-2/3-in. corrugations)	
- Plain	0.022 - 0.026
- Paved invert	0.018 - 0.022
- Spun asphalt lined	0.011 - 0.015
Plastic pipe (smooth)	0.011 - 0.015
Vitrified clay	
- Pipes	0.011 - 0.015
- Liner plates	0.013 - 0.017

Figure D.2: Runoff coefficients fro closed conduits. [28]

Appendix E: IDF

	10'-2years	10'-10years	10'-25years
00:01:00	7,5	15,36	25,2
00:02:00	7,5	15,36	25,2
00:03:00	7,5	15,36	25,2
00:04:00	7,5	15,36	25,2
00:05:00	7,5	15,36	25,2
00:06:00	7,5	15,36	25,2
00:07:00	7,5	15,36	25,2
00:08:00	7,5	15,36	25,2
00:09:00	7,5	15,36	25,2
00:10:00	7,5	15,36	25,2

Table E.1: Intensity of rain [mm/h] for rain of t_r = 10 min and T_r = 2, 10, 25 years.

	2h-10years	2h-25years
00:05:00	4,5	5,3
00:10:00	4,5	5,3
00:15:00	4,5	5,3
00:20:00	4,5	5,3
00:25:00	4,5	5,3
00:30:00	4,5	5,3
00:35:00	7,8	8,8
00:40:00	7,8	8,8
00:45:00	7,8	8,8
00:50:00	23,4	30,6
00:55:00	34,2	42,6
01:00:00	79,8	100,8
01:05:00	79,8	100,8
01:10:00	34,2	42,6
01:15:00	23,4	30,6
01:20:00	7,8	8,8
01:25:00	7,8	8,8
01:30:00	7,8	8,8
01:35:00	4,5	5,3
01:40:00	4,5	5,3
01:45:00	4,5	5,3
01:50:00	4,5	5,3
01:55:00	4,5	5,3
02:00:00	4,5	5,3

Table E.2: Intensity of rain [mm/h] for rain of $t_r = 2$h and $T_r = 10$, 25 years.

Whole bibliography

[1] URL: https://www.epa.sa.gov.au/files/7492_urban_water_cycle.jpg (visited on 06/02/2023).

[2] *Guide technique pour le dimensionnement des ouvrages de rétention*. URL: https://www.giser.be/wp-content/uploads/2019/05/Guide-technique-Eaux-pluviales.pdf.

[3] *0QLYh.png (800×1216)*. URL: https://i.stack.imgur.com/0QLYh.png (visited on 06/02/2023).

[4] *800px-Groundwater_flow.svg.png (800×496)*. URL: https://upload.wikimedia.org/wikipedia/commons/thumb/c/c7/Groundwater_flow.svg/800px-Groundwater_flow.svg.png (visited on 06/02/2023).

[5] Sahar Babaei, Reza Ghazavi, and Mahdi Erfanian. "Urban flood simulation and prioritization of critical urban sub-catchments using SWMM model and PROMETHEE II approach". In: *Physics and Chemistry of the Earth, Parts A/B/C*. The 17th WaterNet/WARFSA/GWPSA Symposium: Integrated Water Resources Management: Water Security, Sustainability and Development in Eastern and Africa Southern 105 (June 1, 2018), pp. 3–11. ISSN: 1474-7065. DOI: 10.1016/j.pce.2018.02.002. URL: https://www.sciencedirect.com/science/article/pii/S1474706517301584 (visited on 06/01/2023).

[6] Yiran Bai et al. "Storm Water Management of Low Impact Development in Urban Areas Based on SWMM". In: *Water* 11.1 (Jan. 2019). Number: 1 Publisher: Multidisciplinary Digital Publishing Institute, p. 33. ISSN: 2073-4441. DOI: 10.3390/w11010033. URL: https://www.mdpi.com/2073-4441/11/1/33 (visited on 06/01/2023).

[7] João Barreiro et al. "Index-based Approach to Evaluate City Resilience in Flooding Scenarios". In: *Civil Engineering Journal* 7.2 (Feb. 1, 2021). Number: 2, pp. 197–207. ISSN: 2476-3055. DOI: 10.28991/cej-2021-03091647.

URL: https://www.civilejournal.org/index.php/cej/article/view/2644 (visited on 06/01/2023).

[8] B. Barroca et al. "Indicators for identification of urban flooding vulnerability". In: *Natural Hazards and Earth System Sciences* 6.4 (June 23, 2006). Publisher: Copernicus GmbH, pp. 553–561. ISSN: 1561-8633. DOI: 10.5194/nhess-6-553-2006. URL: https://nhess.copernicus.org/articles/6/553/2006/ (visited on 06/01/2023).

[9] *Données des réseaux Collecteurs et Egouttages*. URL: https://ipalle-oneline.maps.arcgis.com/apps/webappviewer/index.html?id=a38887023e724139a1de0049bca6e637 (visited on 06/03/2023).

[10] *HumanIntegratedWaterCycle_(2).jpg (2997×1747)*. URL: https://upload.wikimedia.org/wikipedia/commons/7/73/HumanIntegratedWaterCycle_%5C%282%5C%29.jpg (visited on 06/02/2023).

[11] Institut Bruxellois pour la gestion de l'environnement IBGE. "Comment favoriser l'infiltration de l'eau dans le sol?" In: (). URL: https://document.environnement.brussels/opac_css/elecfile/IF%5C%20Eco-construction%5C%20EAU03%5C%20Part%5C%20Fr.

[12] *IRM - Observations historiques d'inondations jusqu'à la fin du 19ème siècle (première partie)*. KMI. URL: https://www.meteo.be/fr/infos/actualite/observations-historiques-dinondations (visited on 06/01/2023).

[13] Anna Kis et al. "Application of RCM results to hydrological analysis". In: *Idojaras* 121 (Oct. 1, 2017), pp. 437–452.

[14] *LGCIV2051: pdf files of the slides form the videos*. URL: https://moodle.uclouvain.be/mod/folder/view.php?id=35448 (visited on 06/02/2023).

[15] Ganquan Mao and Junguo Liu. "WAYS v1: a hydrological model for root zone water storage simulation on a global scale". In: *Geoscientific Model Development* 12.12 (Dec. 17, 2019). Publisher: Copernicus GmbH, pp. 5267–5289. ISSN: 1991-959X. DOI: 10.5194/gmd-12-5267-2019. URL: https://gmd.copernicus.org/articles/12/5267/2019/ (visited on 06/02/2023).

[16] Maryam Hassan Mohammed, Haider M. Zwain, and Waqed Hammed Hassan. "Modeling the impacts of climate change and flooding on sanitary sewage system using SWMM simulation: A case study". In: *Results in Engineering* 12 (Dec. 1, 2021), p. 100307. ISSN: 2590-1230. DOI: 10.1016/j.rineng.2021.100307. URL: https://www.sciencedirect.com/science/article/pii/S2590123021001080 (visited on 06/01/2023).

[17] B. K. Nile, W. H. Hassan, and B. A. Esmaeel. "An evaluation of flood mitigation using a storm water management model [SWMM] in a residential area in Kerbala, Iraq". In: *IOP Conference Series: Materials Science and Engineering* 433.1 (Nov. 2018). Publisher: IOP Publishing, p. 012001. ISSN: 1757-899X. DOI: 10.1088/1757-899X/433/1/012001. URL: https://dx.doi.org/10.1088/1757-899X/433/1/012001 (visited on 06/01/2023).

[18] phuoc. *Hydrology and Water Management Applications of GCIP Research*. SlideServe. Sept. 9, 2014. URL: https://www.slideserve.com/phuoc/hydrology-and-water-management-applications-of-gcip-research (visited on 06/02/2023).

[19] *Rational Method Runoff Coefficient - CivilWeb Drainage Design Spreadsheets*. CivilWeb Spreadsheets. URL: https://civilweb-spreadsheets.com/drainage-design-spreadsheets/runoff-and-rainfall-intensity-calculator-spreadsheet/rational-method-runoff-coefficient/ (visited on 06/01/2023).

[20] Marlène Rio, Christian Salles, and Marie-George Tournoud. "Modelling the effects of stormwater control measures on runoff volume and particulate load in urban catchments". In: *Urban Water Journal* 18 (Dec. 22, 2020), pp. 1–12. DOI: 10.1080/1573062X.2020.1860236.

[21] Marlène Rio et al. "An original urban land cover representation and its effects on rain event-based runoff and TSS modelling". In: *Journal of Hydrology* 586 (July 1, 2020), p. 124865. ISSN: 0022-1694. DOI: 10.1016/j.jhydrol.2020.124865. URL: https://www.sciencedirect.com/science/article/pii/S0022169420303255 (visited on 06/01/2023).

[22] Hannah Ritchie, Pablo Rosado, and Max Roser. "Natural Disasters". In: *Our World in Data* (Dec. 7, 2022). URL: https://ourworldindata.org/natural-disasters (visited on 06/01/2023).

[23] Hannah Ritchie and Max Roser. "Water Use and Stress". In: *Our World in Data* (Nov. 20, 2017). URL: https://ourworldindata.org/water-use-stress (visited on 06/01/2023).

[24] Fazal Shaik and Sunny Agarwal. "Urban Flood Modeling and Management using SWMM for New R.R. Pet Region, Vijayawada, India". In: (June 2, 2019).

[25] Sandra Soares Frazao. *LGCIV2051 Applied hydraulics, UCLouvain 2021*.

[26] "Statistiques des précipitations extrêmes des communes belges Mouscron (ins 54007)". In: 9 (Sept. 2012), 2011WR011707. ISSN: 0043-1397, 1944-7973. DOI: 10.1029/2011WR011707. URL: https://opendata.meteo.be/ftp/climate/extreme_precipitations/IDF_table_INS54007_fr.pdf (visited on 06/01/2023).

[27] *Swmm Apps Manual - [PDF Document]*. vdocuments.net. URL: https://vdocuments.net/swmm-apps-manual.html (visited on 06/02/2023).

[28] ORD US EPA. *Storm Water Management Model (SWMM) version 5.1 User's Manual*. Feb. 13, 2019. URL: https://www.epa.gov/water-research/storm-water-management-model-swmm-version-51-users-manual (visited on 06/02/2023).

[29] *water-cycle.jpg (1800×1223)*. URL: https://www.bcwater.org/wp-content/uploads/2020/05/water-cycle.jpg (visited on 06/02/2023).

[30] Wei Xing et al. "Layout effects and optimization of runoff storage and filtration facilities based on SWMM simulation in a demonstration area". In: *Water Science and Engineering* 9.2 (Apr. 1, 2016), pp. 115–124. ISSN: 1674-2370. DOI: 10.1016/j.wse.2016.06.007. URL: https://www.sciencedirect.com/science/article/pii/S1674237016300199 (visited on 06/01/2023).

UNIVERSITÉ CATHOLIQUE DE LOUVAIN
École polytechnique de Louvain
Rue Archimède, 1 bte L6.11.01, 1348 Louvain-la-Neuve, Belgique | **www.uclouvain.be/epl**