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Application of LID on the VUB Campus

Report for Assignment 2

Introduction

SWMM is a widely-used software that allows the user to build models of sewer systems by implementing junctions, conduits, rain gages, sub-catchments and more. It also allows the implementation of different forms of LID such as permeable pavement, green roofs, and rain gardens. Permeable pavement can be used to locally infiltrate stormwater and reduce effective water impermeability, it is good at reducing runoff volume and decreasing the flooding happening downstream, it has the advantage to achieve the natural conditions through the drainage of paved areas. Green roofs are multi-beneficial structures that help to reduce the runoff volume and peak discharge rate (Berghage et al., 2009), it can eliminate the effects of urbanization on water quality by filtering as well. Mostly they are installed on the roof of the building, it has the advantages of low cost, easy installation and maintenance.

The aim of this assignment is to create a SWMM model of the sewer system of the VUB campus in order to consider different LID measures that would solve the outflow problem caused by the new buildings. Since the outflow of the storm sewer system of the VUB campus must be limited to 115 l/s, the system is facing a challenge with the new campus layout under some big storms. In 2015, new buildings were added to the campus, which increased the storm flow. To limit this outflow, a solution called Low Impact Developments, or LID is suggested to be implemented on the campus.

Methods & Results

The main process of LID application for this task is divided into four stages, and the detailed methods and results are stated here. First step is to build a composite design storm considering our return period of 25 years. Secondly, we will create a SWMM model of the existing storm sewer system and analyze the results obtained with it. Then, we will extend the sewer system to take into account the flow added by the new buildings, and analyze the results obtained with it. Finally, a plan for the application of LID to our system is completed before performing a control calculation.

1. *Creation of the composite design storm*

The creation of the composite design storm is based on the given return period and Ukkel Intensity Duration Frequency relationships data(Chow et al.,1988). The composite storm is that the maximum intensities that are averaged over a certain duration are the same as the values obtained in the IDF curves. In this task, the return period is determined as 25 years. Then the **duration time** is considered as **120 minutes** with a **5-minute** interval since the model simulation result is best under this condition. Since we have tried for 70 mins and 35 mins, we are not satisfied with the results. After calculating the cumulative depth and the incremental depth (Table 1), the precipitation for each short interval is rearranged (Table 2). The method used to arrange the precipitation is based on the features of the rainfall in Brussels (Borsanyi, P. et al.,2008), and the intensive precipitation is considered as in the mid-time. The calculation results are plotted in Figure. 1 and the rainfall is in an asymmetrical distribution.

Table.1 - The design composite storm calculations, using the alternating block method.

Time(min)	***Intensity(mm/h)***	***Intensity(mm/min)***	***Cumulated depth(mm)***	***Incremental depth(mm)***
120	*18.71*	*0.31*	*37.41*	*0.33*
115	*19.35*	*0.32*	*37.08*	*0.35*
110	*20.04*	*0.33*	*36.73*	*0.37*
105	*20.78*	*0.35*	*36.36*	*0.39*
100	*21.59*	*0.36*	*35.98*	*0.41*
95	*22.46*	*0.37*	*35.56*	*0.44*
90	*23.42*	*0.39*	*35.13*	*0.47*
85	*24.47*	*0.41*	*34.66*	*0.50*
80	*25.62*	*0.43*	*34.17*	*0.53*
75	*26.90*	*0.45*	*33.63*	*0.61*
70	*28.30*	*0.47*	*33.02*	*0.63*
65	*29.90*	*0.50*	*32.39*	*0.69*
60	*31.70*	*0.53*	*31.70*	*0.72*
55	*33.80*	*0.56*	*30.98*	*0.82*
50	*36.20*	*0.60*	*30.17*	*0.92*
45	*39.00*	*0.65*	*29.25*	*1.05*
40	*42.30*	*0.71*	*28.20*	*1.19*
35	*46.30*	*0.77*	*27.01*	*1.36*
30	*51.30*	*0.86*	*25.65*	*2.03*
25	*56.70*	*0.95*	*23.63*	*1.63*
20	*66.00*	*1.10*	*22.00*	*2.50*
15	*78.00*	*1.30*	*19.50*	*3.33*
10	*97.00*	*1.62*	*16.17*	*4.98*
5	*134.20*	*2.24*	*11.18*	*11.18*

Table.2 - The rearranged rainfall for the composite design storm.

Time(min)	***Rainfall(mm)***	***Time(min)***	***Rainfall(mm)***
0-5	0.33	60-65	11.18
5-10	0.37	65-70	3.33
10-15	0.41	70-75	2.03
15-20	0.47	75-80	1.36
20-25	0.53	80-85	1.05
25-30	0.63	85-90	0.82
30-35	0.72	90-95	0.69
35-40	0.92	95-100	0.61
40-45	1.19	100-105	0.50
45-50	1.63	105-110	0.44
50-55	2.50	110-115	0.39
55-60	4.98	115-120	0.35

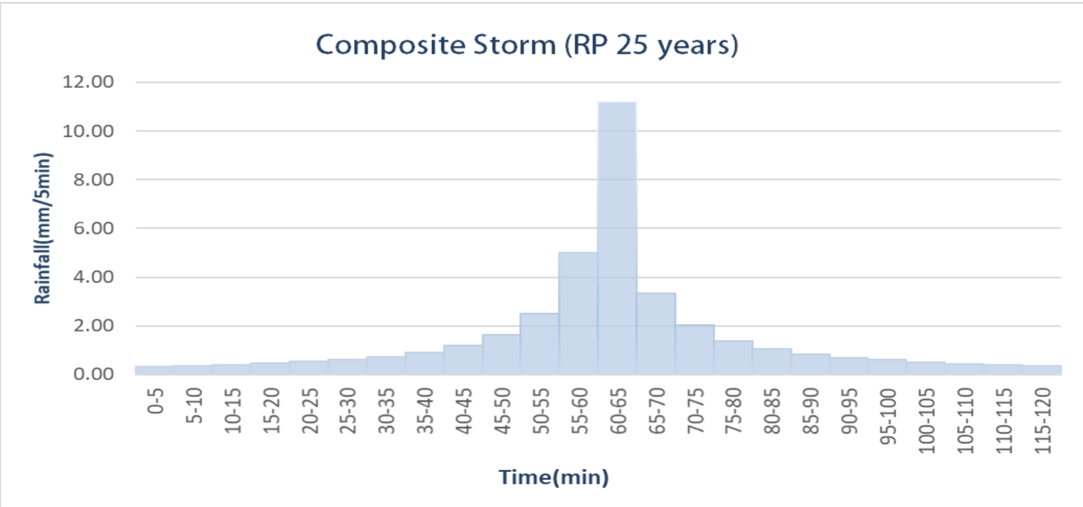

Figure.1 - The plot of the composite storm design.

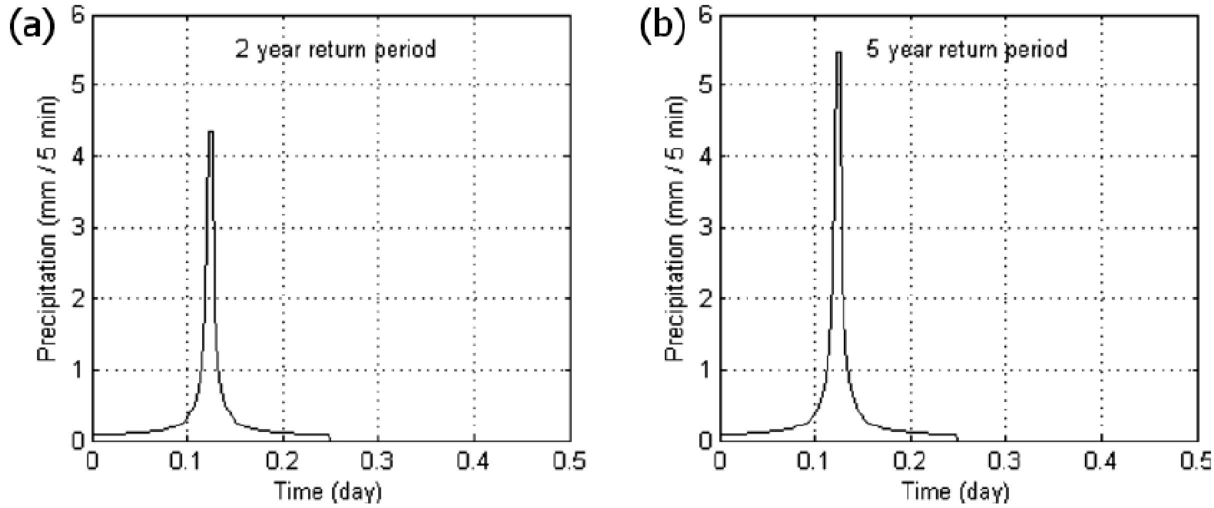

Figure.2 - The Flemish (Belgium) composite design storms with (a) 2 years return period and (b) 5 years return period (Borsanyi, P. et al.,2008).

1. Creation of a SWMM model of the existing sewer system

To build the sewer network in SWMM, we add several objects to our system, consisting of Junctions, conduits, rain gages, outfall, sub-catchments, pump, weir, and storage.

a. Junctions, Conduits, Outfall and Rain gage

There are 48 junctions, from number 1 to 48, accordingly, the same number of conduits were added to connect each junction, the shape of conduits is circular. There is one outfall node placed at the end of the sewer system, which is considered a free outfall. In addition, the rain gauge was used to monitor the rainfall data in the study region.

b. Sub-catchments

For easier implantation of LID, we decided to divide the sub-catchments into three types: the impervious sub-catchments corresponding to the buildings, the impervious sub-catchments corresponding to the roads, and the previous sub-catchments.

i. Buildings

In order to calculate the sub-catchment areas corresponding to the buildings, we had access to an AutoCAD file of the campus. Using this file, we measured the surface of each building's roof. Then, we associated these buildings to the nodes they were the closest with. The sub-catchment area of an outlet then depends on a linear combination of fractions of the roof areas of the buildings it is associated with. To calculate the width of the sub-catchments, we had to determine the longest overland flow distance traveled by the water, which we estimated as the distance between the outlet and the farthest building's farthest corner. After measuring this distance in AutoCAD, we simply divided the area by it to obtain the width. For the slope, we used a value of 0.01% for every building, because even if every roof on the campus is flat, we need to implement a slope value for the simulation to work. For the value of Manning's n, we used a typical value of 0.013 for the smooth concrete the roofs are made out of.

ii. Roads

To determine the sub-catchment areas relative to the roads, we used the values given for the impervious area associated with each node. We simply subtracted the calculated areas of the sub-catchments associated with the buildings to the total impervious area. Then, we determined the width using once again the longest overland flow. By tracing the road sub-catchment for the first outlet, we estimated the longest overland flow at 80 m for this first point. Since this length is mostly dependent on the road's width, we used this value of 80 m for each outlet associated with a road having the same width and adapted this value for the different road widths that occur along with the system. For example, for the roads that were two times smaller than the road associated with outlet 1, we used a value of 160 m for the longest overland flow. We made an estimation of the slope by using the ground levels and lengths given for each node and applying the typical $\frac{vertical\ displacement}{horizontal\ displacement}$ formula between the subcatchment's outlet and another node in its area. For Manning's n, we used a typical value of 0.011 for the concrete the roads are made out of.

iii. Pervious sub-catchments

First, we import the stream net and elevation map of the study area on QGIS. By observation the elevation, the distribution of the stream network, and the direction of the water flow, we select 13 representative points in the entire area, after adding the coordinates of each point in WETSPA and running this project, the entire area was divided into 13 sub-catchments shown in Fig.3. Besides, it generated the land use map (Fig.4) for each sub-catchment as well, which provides 4 kinds of land uses, namely tree, grassland, previous land, and a negligible class.

In order to install the previous catchments in the sewer system in SWMM, it is needed to measure the longest overland flow distance, slope, and the previous area of each sub-catchment in QGIS. Firstly, the longest overland flow distance was measured for each sub-catchment, that is, in the farthest distance from the outlet in each catchment, an example shown in the red square in Fig.4. With this value, we calculated the width of the sub-catchments just like we did for the impervious ones. We also estimated the height difference between the highest and the lowest point in each sub-catchment using the elevation map to determine the slope. Secondly, to measure the area of various land-uses in QGIS, the zonal statistics tool was used. The method is to first convert the raster layer of each sub-catchment into polygons, because the resolution of the known map is 2m X 2m, so the area of each pixel is $4m^2$. The next step was to calculate the number of pixels of different land-use in each sub-catchment through the zonal statistic tool. After getting the pixel numbers, multiply with the pixel area to get the land-uses area. The pervious area of each sub-catchment can get from adding up the area of trees and grassland. To implement the heterogeneity of land-use in each sub-catchment, we calculated Manning's n by ponderating each land-use associated n with the fraction of the surface it represents for the entire sub-catchment. For this, we used values 0.15 for the grassland areas, and 0.4 for the trees that we found in the help topics of SWMM.

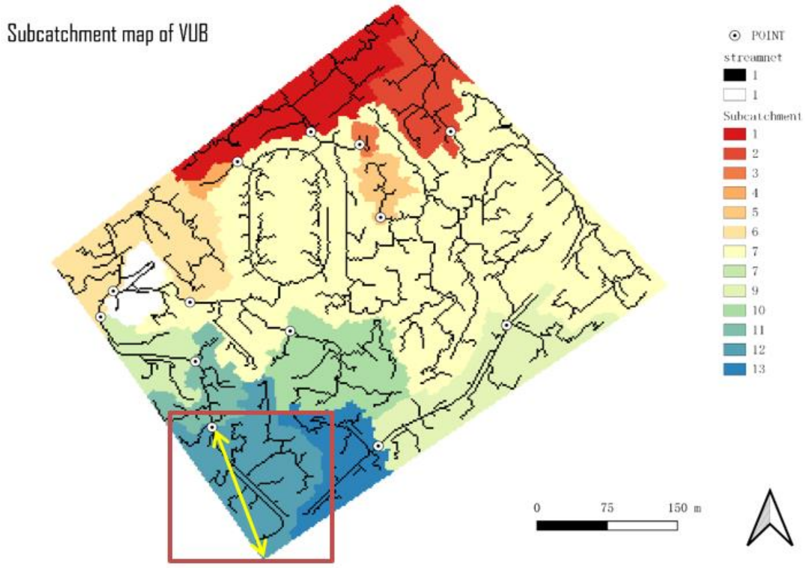

Figure.3 – Sub-catchment map of VUB around 1985.

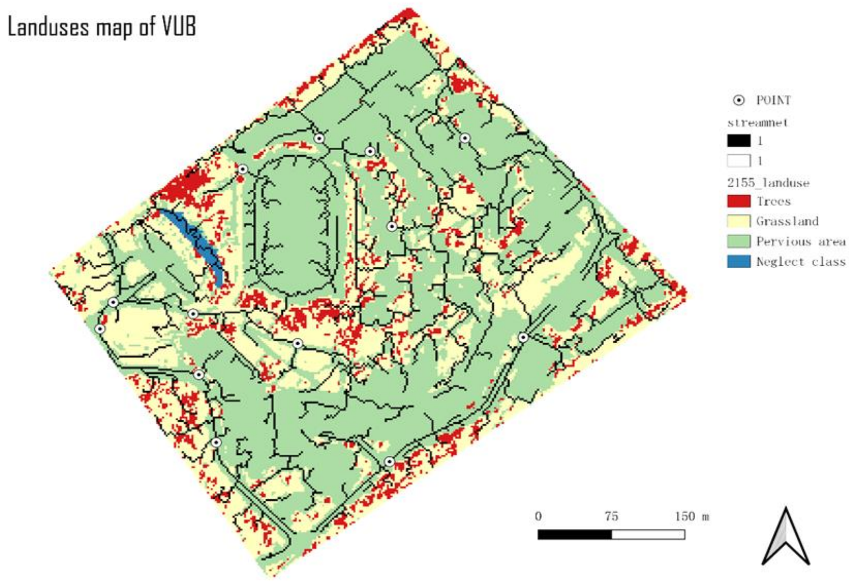

Figure.4 – Land uses map of VUB around 1985.

The values entered in SWMM for the pervious subcatchments can be seen in the table below:

Table. 3 - The information of the pervious subcatchments.

.	Area (ha)	Width (m)	Slope (%)	N-perv
1	0.576	28	1.96	0.21
6	0.308	23	2.21	0.22
12	0.647	41	1.91	0.19

14	0.222	27	2.44	0.21
17	0.392	28	1.42	0.19
18	0.958	66	0.68	0.19
20	6.1528	65	0.98	0.20
23	0.8384	35	2.04	0.18
32	0.6816	17	0.73	0.22
40	0.184	17	0.68	0.20
44	0.576	28	1.96	0.21
45	0.308	23	2.21	0.22
47	0.647	41	1.91	0.19

c. *Storage, Weir and Pump*

The storage was taken as a node in the sewer system and added between junctions 28 and 29, the aim to place it in the location near the outfall is to prevent the excessive amount of runoff in the outfall. It was designed using the tabular method, thus a storage curve was defined to present the storage volume. In Figure 5, 3 m is the maximum depth of the storage, 1247 m^2 is the surface area of storage measured in AutoCAD. Besides, because the invert elevation of the previous node is 82.33 m, the invert level of storage should be relatively lower than it, after repeatedly trying in the model, we decided to choose 79.7 m as the invert elevation for storage. But due to the invert elevation for the next node being 82 m, which is higher than storage, it is impossible to let the water at the lowest point in the container flow naturally to the next node through gravity, thus, to add a pump between these two nodes was a reasonable choice.

Then, as for the weir, the shape is determined firstly as Transverse with a certain range of discharge coefficient(1.84SI). Then, as for the height and length of the weir, the equation to calculate the weir flow should be considered. After determining the height as 1m, the length is set to 22m. In order to make sure the weir is able to take the maximum flow rate. Finally, the pump design should meet the requirement that $Qtr(t) + Qout(t) \leq Qcrit$. Firstly, we decided to use type 2. Then, the designed pump curve is used to control the flow rate of the pumping system. The flow rate is set to 0.02m^3/s, 0.05m^3/s, 0.08m^3/s when the depth is at 1m, 2m and 3m. Finally, the control lines of code are for setting the conditions of node head when to open or close. The control rules are listed below.

```
RULE 2_ON
IF NODE 28 HEAD >= 81.530000
THEN PUMP 2 STATUS = ON
RULE 2_OFF
IF NODE 28 HEAD <= 81.030000
THEN PUMP 2 STATUS = OFF
```

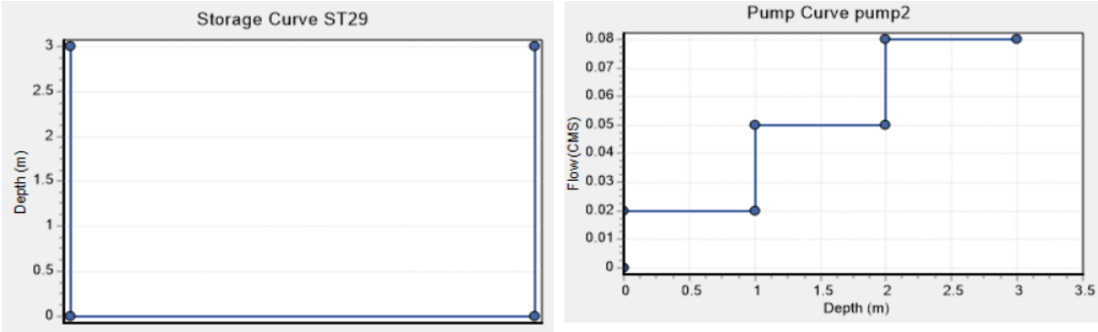

Fig.5 – The storage curve (left) and pump curve (right) of the existing sewer system in SWMM.

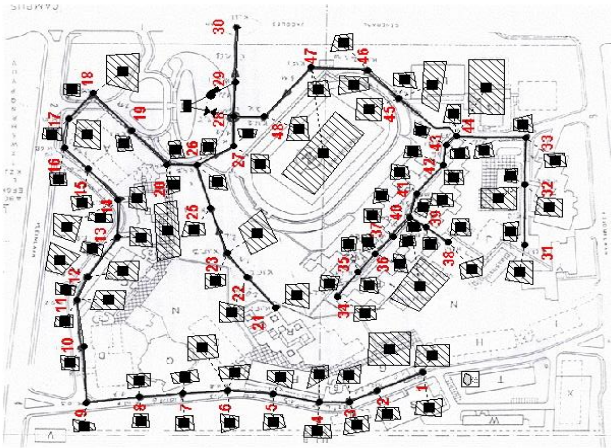

Figure.6 – The existing system of VUB in SWMM.

2. Analysis of the results for the existing sewer system

As mentioned in the introduction, the main element to look out for is the flow arriving in the outfall of the system. On the graphic below, we can see that the maximum flow reaches under 0.115 m^3/s: the existing sewer system was well designed to handle the storms without generating too much outflow.

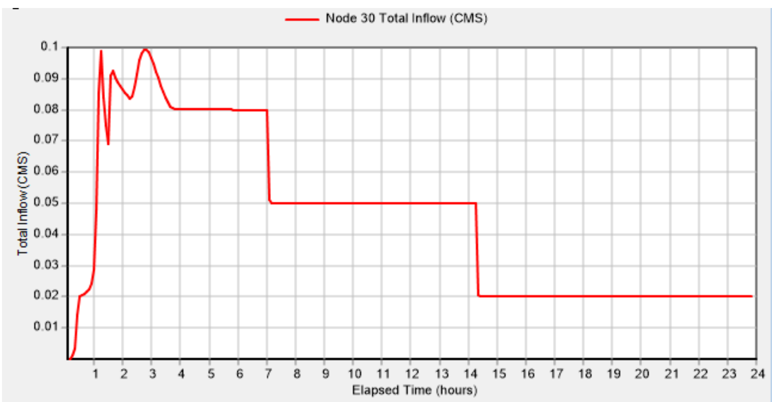

Figure.7 - Outflow of the existing system in SWMM.

Now, we can have a look at water elevation profiles for different sections at the most critical point in time of the system to see which parts have the most impact on the outflow.

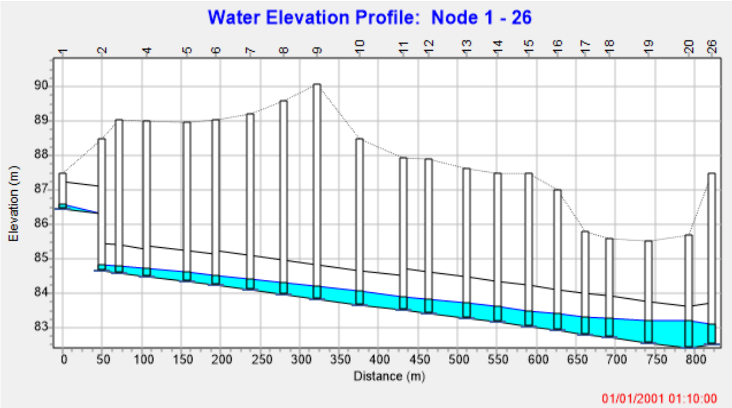

Fig.8 - Water elevation profile between nodes 1 and 26 of the existing system in SWMM

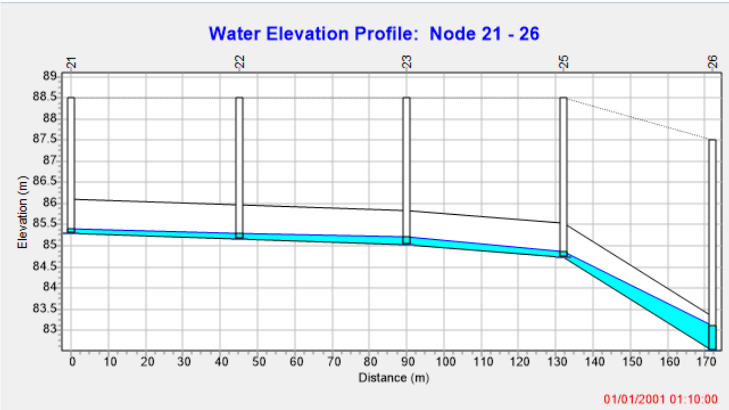

Figure.9 - Water elevation profile between nodes 21 and 26 of the original system

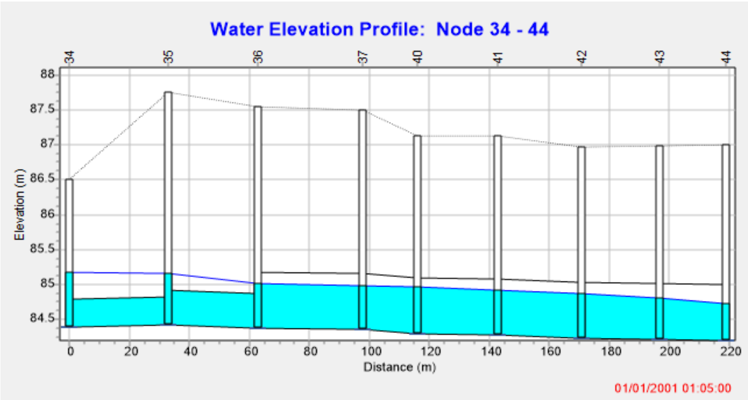

Figure.10 - Water elevation profile between nodes 34 and 44 of the existing system

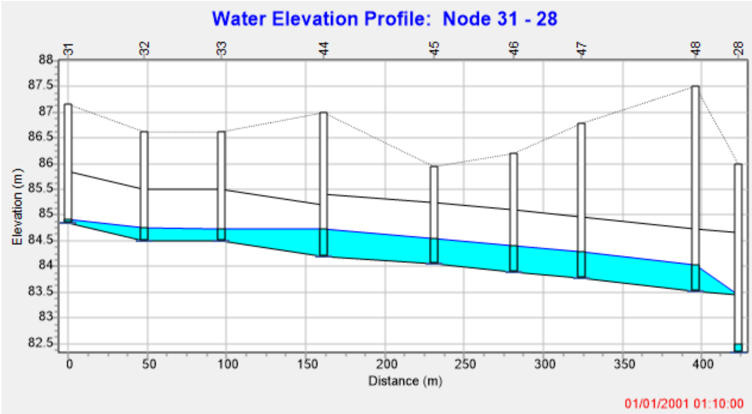

Fig.11 - Water elevation profile between nodes 31 and 28 of the existing system

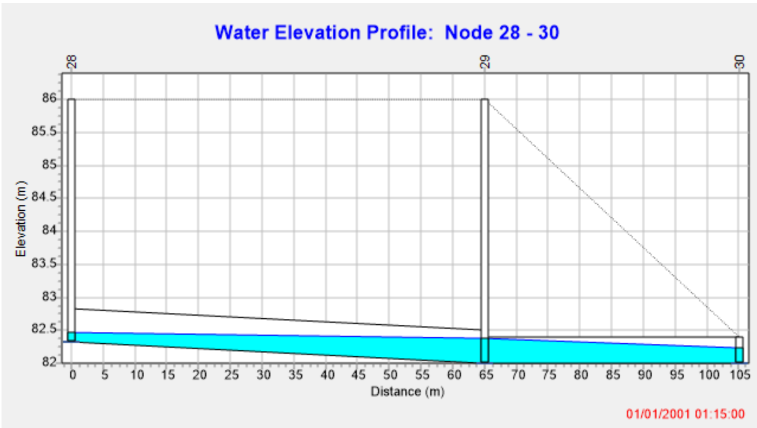

Fig.12 - Water elevation profile between nodes 28 and 30 of the existing system

As we can see on these graphs, the highest elevations can be found between the 34th and 44th nodes, which means for now the most effective way to apply LIDs would be to add them between these points in order to reduce the outflow.

3. Extension of the sewer system

For the extension of the sewer system, an AutoCAD file containing information about the new buildings was given. An overview of the location of each building can be seen in Fig.13 below:

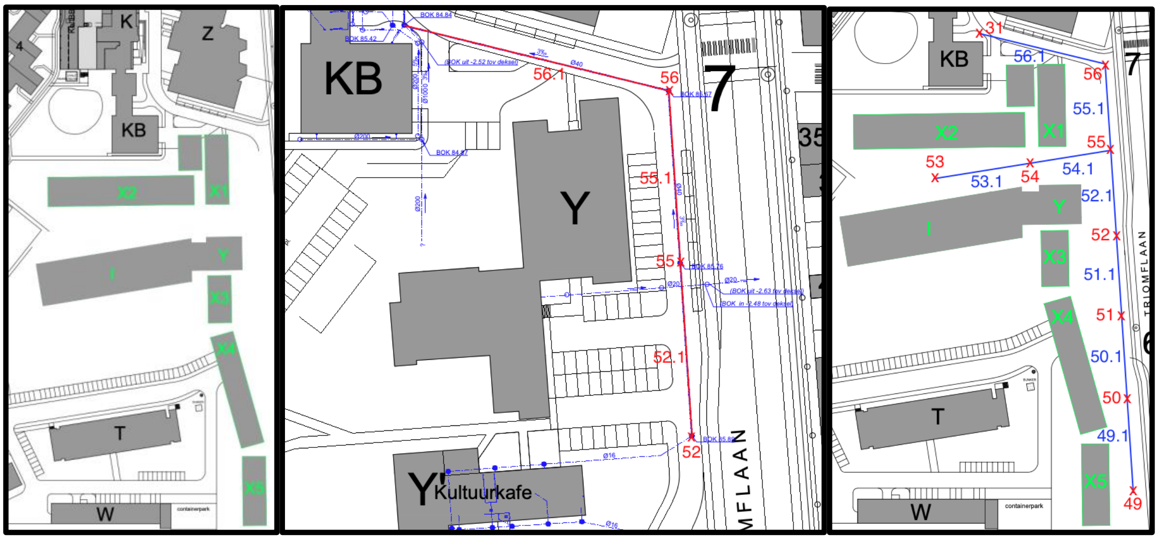

Fig.13 - Display of the new buildings (left), implantation of nodes 52, 55, 56 and associated conduits (middle), implantation of nodes 49-56, 31 and associated conduits (right)

From the original sewer system file, we noticed that different nodes from the original 48 presented in the tables were present. Three of those were around the same area as the new buildings: we decided to implement them into our model, copying their position and level from the file, and extend our system by following a similar pattern. The implantation of those three nodes and the associated conduits can be seen in the map in the middle of Fig. 13.

We decided to add new conduits in the same direction as conduits 52,1 and 55,1, following the line of buildings until the X5 one. To implement the sub-catchment associated with buildings X1, X2, I and Y, we added conduits in the perpendicular direction going through these buildings and connecting to the rest of the extension at node 55. The chosen disposition can be seen in the map on the right of Fig. 13.

The length of conduits 52,1 and 55,1 was 38 meters according to the AutoCAD file: we decided to keep this length for the other conduits which resulted in adding three conduits to reach building X5 and two conduits in between buildings X2/X1 and I/Y. For the ground level of the nodes created, we used approximations from the elevation map. We then chose the invert levels in order to have a similar slope in this part as the average slope for the rest of the system. For the size of the pipes, we used a similar disposition as for the first points of the system, which meant we used a diameter of 0.8 m for the beginning of each conduit line and a 0.9 m diameter for the rest, matching the diameter of the 31,1 conduit this extension is connected to. The values entered in SWMM for each point and each junction can be found below:

Table. 4 – The length and max depth of conduit 49.1 to 56.1

Conduit	Length	Max depth (m)
49,1	38	0.8
50,1	38	0.8
51,1	38	0.8
52,1	38	0.9
53,1	38	0.8
54,1	38	0.8
55,1	38	0.9
56,1	59	0.9

For the sub-catchments, we used the same approach as for the building sub-catchments of the original system: we associated each building to the closest outlets, calculated the width similarly and used the same values for the slope and Manning's n. The values entered in SWMM for each subcatchment can be found below:

Table. 5 – The area and width of subcatchment outlet 49 to 56

Sub-catchment outlet	Area (ha)	Width (m)
49	0.043	11
50	0.036	7
51	0.036	7
52	0.044	9
53	0.194	32
54	0.126	17
55	0.029	5
56	0.015	3

An overview of the implantation of this extension in SWMM can be seen below:

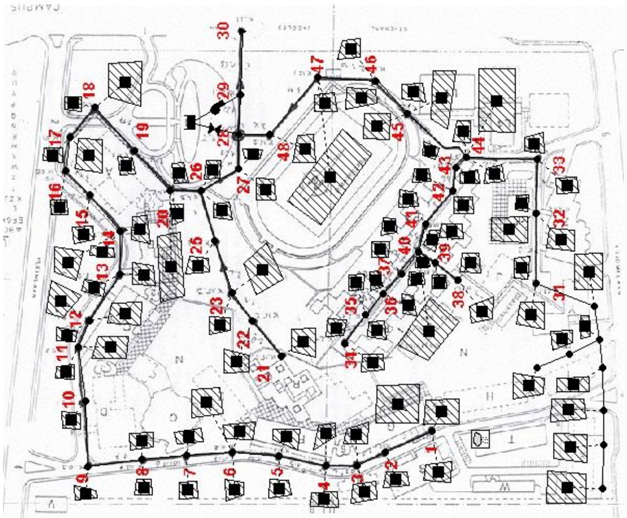

Figure.14 – Extended sewer system of VUB in SWMM

4. Analysis of the results for the extended sewer system

As we can see on the graphic below, the outflow of the sewer system is going over the limit value of 0.115 m^3/s for the extended sewer system.

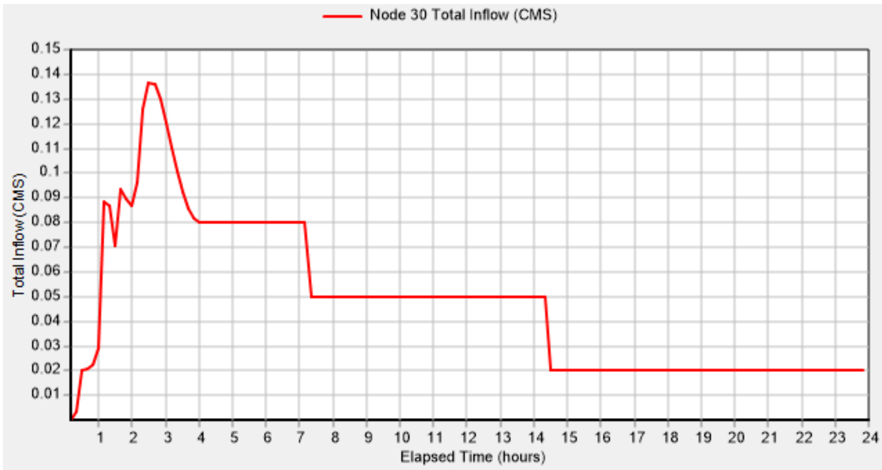

Figure.15 - Outflow of the extended system in SWMM

Although, the added runoff from the new buildings does not seem like a lot from the water elevation graph of the extension below, even at the most critical point.

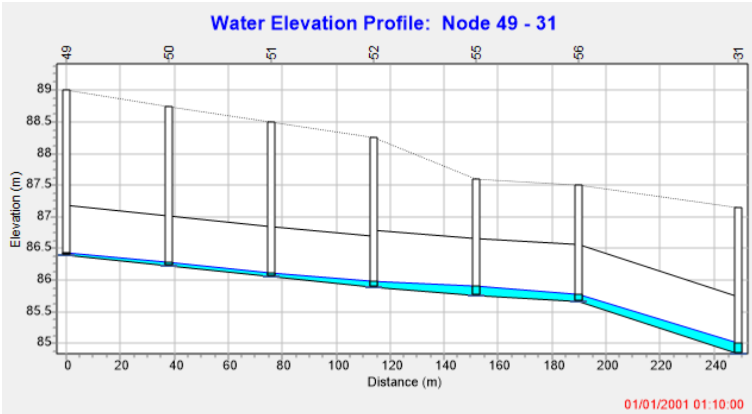

Fig.16 - Water elevation profile of the extension in SWMM

On the graphs below representing the parts of the existing sewer system affected by the extension, we can see that the difference is small with the original model's results. Only the elevation in conduits 31.1 and 32.1 have really grown, but there was already room in those conduits anyways.

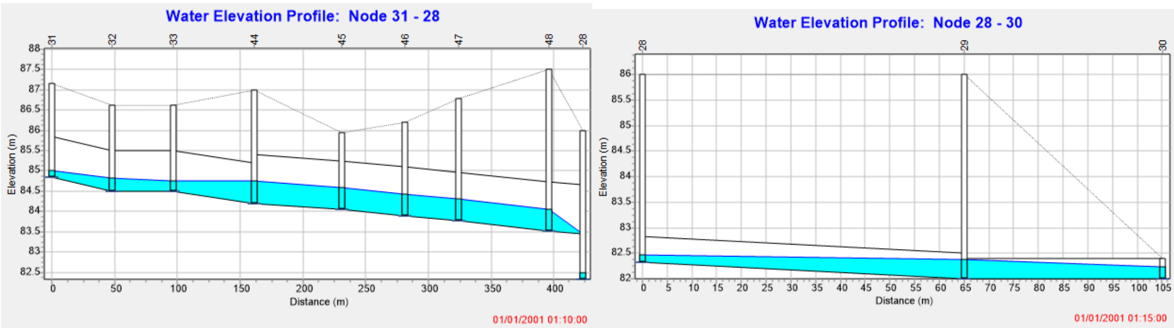

Fig.17- Water elevation profile between nodes 31 and 28 (left) and between nodes 28 and 30 (right) of the extended system

5. Consideration of LID measures to reduce the flows on the campus

LID aims at creating a hydrologically functional landscape, which can minimize impervious land disturbance, enhance infiltration/filtration. The desired result is not only a reduction in stormwater runoff, but improvements in water quality as well (Davis, 2005).

While checking the sub-catchment runoff of the extended model, it shows that the peak runoff (m^3/s), the top twenty all belong to road subcatchment, and due to this model still got the 0.27% flow routing error, so the design of LID is mainly aim to decrease the stormwater runoff. Because the permeable pavement plays a major role in transporting increased stormwater runoff, so it is the first choice for designing LIDs. Besides, from the graph of the extended model (Fig.15), it shows a high and steep peak, therefore, we infer that the road sub-catchment with higher peak runoff (m^3/s) can be selected first, besides, as we mentioned before, the nodes 34th to 44th which have the highest elevation means the most effective way to apply LIDs, after considering the factors of minimizing economic and labor costs, we finally choose to install permeable pavement in the following 6 road sub-catchments shown in Fig.18: R9, R10, R35, R36, R37, R40. After the installation of LIDs, the total inflow at the outfall decreased to around 0.098m3/s (Fig.19), which is relatively lower than the limits 0.115 m3/s, the highest peak total inflow at the outlet decreased significantly, and the peak shape become more rounded and smoother, which will help the sewer system able to handle short bursts of high-intensity rainfall than before.

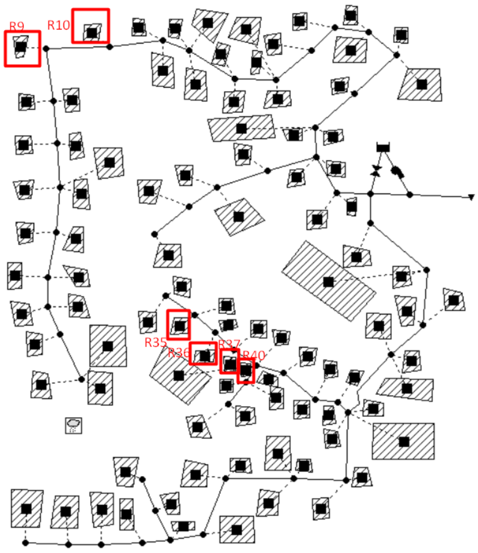

Fig.18 - The selection of the road sub-catchments in extended system for installing the permeable pavement

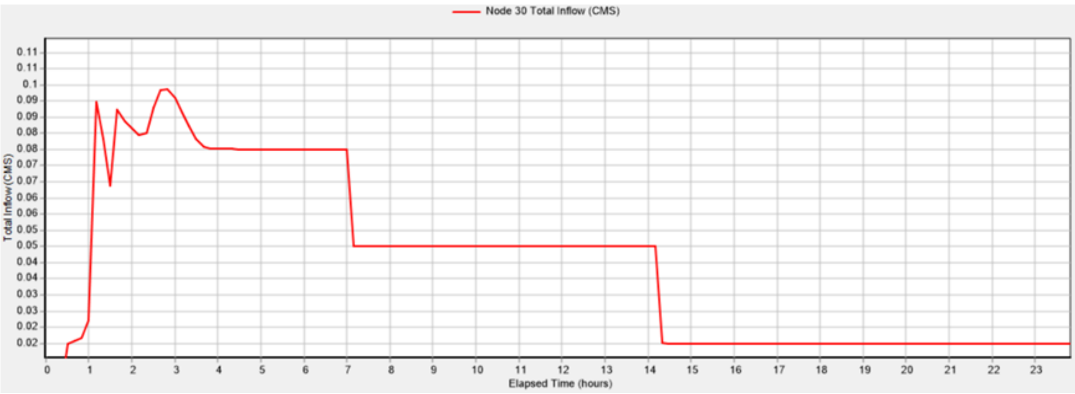

Fig.19 - The total inflow in outfall for LID model with designed storm

6. Control calculation using the rainfall time series of Ukkel station

The last step is using the 2-year rainfall time series of the Ukkel station for the control simulation, and the input data file for this simulation is called the Ukkel.dat. In the status report, the errors for runoff quantity continuity and flow routing continuity is similar to the designed storm simulation. It is obvious that the runoff quantity continuity error values with a designed storm in both the original model and LID completed model are below zero, which is opposite to the results of the control simulation. Also, for the flow routing continuity, the values are within the reasonable range as shown in table 6. For most rainfall situations in 2001 and 2002, the flow is below the limited level(115l/s). However, the result in Fig.21 shows two peak flows exceeding the maximum level which means the system pipe capacity is not sufficient for this situation. Since in the summer, the extremely high rainfall storm happens once or twice a year, and the normally distributed rainfall is much lower than the storm level. So it should have great importance to analyze the summer storm based on the features of rainfall in Brussels.

Table6. The status report of simulation for designed storm and control.

Simulation	Runoff Quantity Continuity (%)	Flow Routing Continuity (%)
designed storm(LID)	-0.27	-0.04
control(LID)	-0.31	0.00
designed storm(Original)	-0.35	-0.08
control(Original)	-0.43	0.00

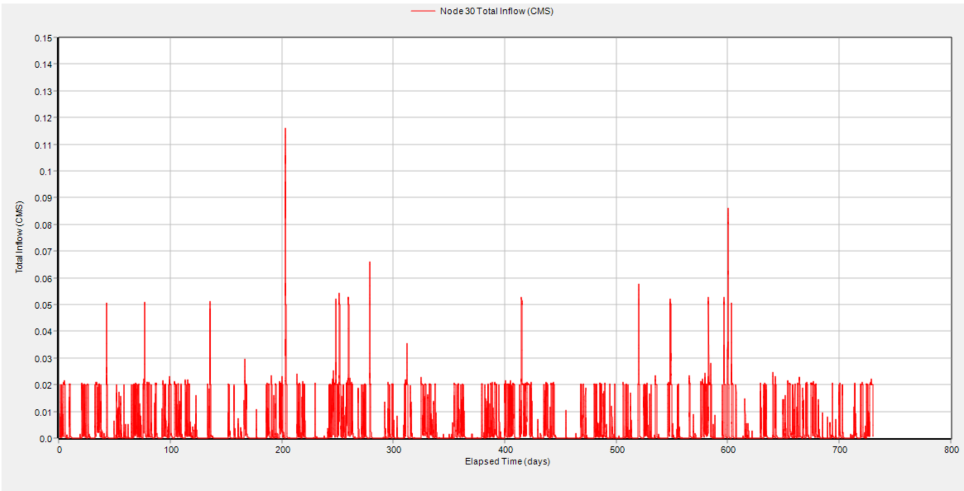

Figure. 21 - The control simulation output using the LID model for the total inflow of Node 30.

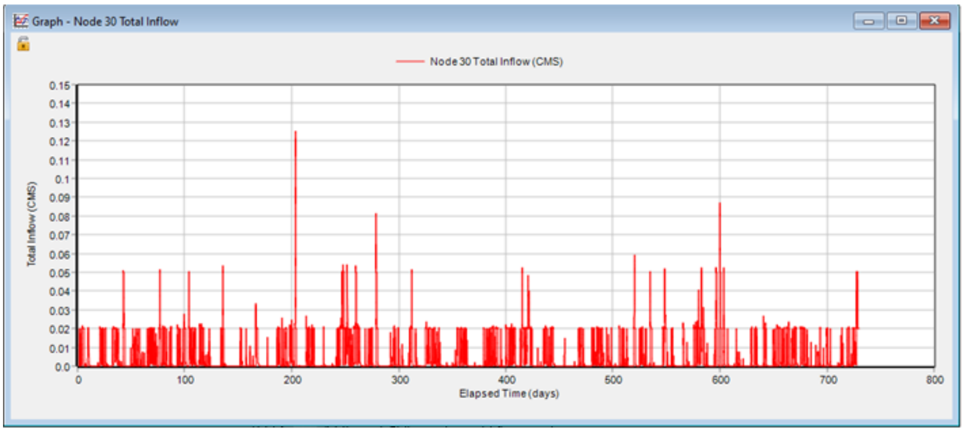

Figure. 22 - The control simulation output using extended model for the total inflow of Node 30.

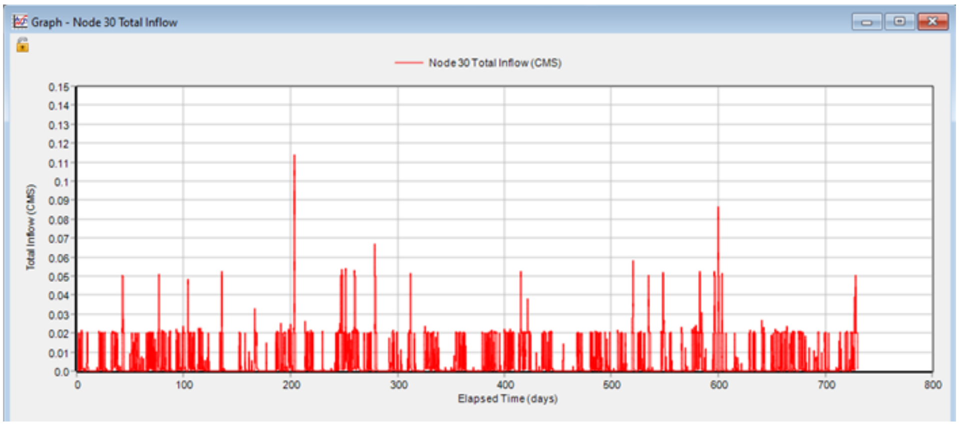

Figure. 23 - The control simulation output using the existing model for the total inflow of Node 30.

Discussion & Conclusion

The designed composite storm plays an important role in the model. However, from the exceedingly high flow in the outflow pipe of the control simulation, it is important to have a properly designed storm. There are two aspects considered, one is the determined duration of the storm, and the other is the rearranged order or the distribution of the precipitation in each minute. As for the storm rearrangement, we consider the shape of the precipitation with a return period of 2 years. However, the Ukkel data shows that the distribution shape of intensive storms could be varied a lot. For example, during a big storm between two peaks, there could be a very short break with very low precipitation. In the system design, some nodes show small errors in the continuity report. This issue means the determining elevation for some nodes could be improved. Also, the continuity error might influence the pipe flow and several large elevation drops are dangerous for increasing the flow velocity and damaging the pipes. The original SWMM model without the buildings has a lower peak inflow in the outflow node which is less than 115l/s. By contrast, the extended SWMM with the new buildings has a higher flow peak than 115l/s, which indicates the need for applying measurements to limit this within 115l/s. Besides, we analyze the results of the two models with a designed storm and the analysis suggests which structures have high potential to add LID.
Finally, the LID design is considered as the tool to decrease the flow in the outflow pipe. Also, we need to consider the most effective way to reach this goal. By comparing the functional effectiveness of the green roof and permeable pavement, it is determined that the permeable pavement is more effective and convenient for our case. Then, we choose the method as LID types applied in the roads selected. As for the control calculation, the status report result is similar to the designed simulation, which means the model is acceptable. However, the thing could happen that the extreme storm cannot meet our design standard, since our return period is 25 years which much longer than the control data time range (2 years). This could be considered as the result of the simulation is not very satisfactory.
In conclusion, the assignment for the application of LID on VUB campus gives us a deep understanding for the application of SWMM and an overview about the storm sewer system design with a certain return period. Besides, we find some issues in the design process such as storm design if using a time series as input. Last but not least, the model is not very stable, so we should consider many aspects such as the elevation drop and the slope. For the LID part, our design could be improved. If possible, the cost and the benefits could be considered while making the plan.

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