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Territorial, Urban, Environmental and Landscape Planning
Curriculum: Planning for the Global Urban Agenda

Master's Thesis

Urban Stormwater Management by Recovery of Abandoned Canals and LID Systems. A case study in Venaria Reale (TO)

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Abstract

Over the course of the last few decades, urban flood catastrophes caused by unexpected significant rains as a result of climate change, have become an increasingly intense issue. Mathematical modelling and simulation have provided the researchers with preventive solutions by real and predictive periodic precipitation data that not only reduced the threat to urban public and private safety but also allowed them to conduct timely decision-making to address and control surface runoff. Thus, numerous mathematical models with acceptable accuracies have been developed to reduce the probable disasters caused by surface runoffs. In this thesis, with focus on Venaria Reale (VR) as a case study, a mixed-method approach was employed based on observational, data analysis, and quantitative survey methods in which Storm Water Management Model (SWMM) and Geographic Information System (GIS) were incorporated to obtain an accurate nature-based solution. Moreover, in the mathematical simulations, the application of Green Infrastructure (GI) was evaluated while reusing the abandoned, yet available, ancient channels and sewer systems in the city. Moreover, the capability of the sewer system was evaluated based on precipitation data, known as Design Rainfall (DR), and Recorded Rainfall (RR) in case of developing proper water pathways from the sewer system to the abandoned channel (Druento Channel). This is also aligned with the integration of the unexecuted Life20 CCA project with the UN Sustainable Development Goals (SDGs). The simulations and analyses were conducted based on three different scenarios: a) Scenario_00, which addressed challenges resulting from significant rainfall, as confirmed by testimonies from the municipality of VR; b) scenario_01 with focus on the resizing Druento channel and evaluating the effectiveness of water pathways originated from the sewer system; c) Scenario_02 that aimed at highlighting the application and efficiency of Low Impact Development (LID) practices in decreasing surface runoff and providing an economical estimation. The obtained results based on DR data indicated that the peak runoffs increased up to 75.4%, 12.22%, 5.47%, and 5.14% after avoiding the application of the influences of green roof, rain garden, permeable pavement, and the bio-retention cell, respectively. Moreover, the results within RR data showed that dismissing the green roofs led to an increase in the peak runoff by 19.36%, while that for rain gardens, bio-retention cells, and permeable pavement were 12.99%, 3.88%, and 2.26% increase, respectively. Additionally, the lowest cost estimation figure was related to the urgent intervention equalling to €2,374,717.80. Whereas by considering 80% of green roofs as a preventive solution, this number rose to €10,893,312.90 and in case half of this figure is applied, the final estimated cost will stand at €6,381,264.90. It indicated that although the implementation of green roofs consumes the majority of the budget, it plays the most significant role in controlling surface runoffs and potential flood damages.

Keywords: Geography Information System, Storm Water Management Model, Low Impact Development, Urban Flooding, Green Infrastructure, Sustainable Urban Development

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Contents

Glossary of terms

Venaria Reale	VR
Storm Water Management Modelling	SWMM
Geographic Information System	GIS
Green Infrastructure	GI
Design Rainfall	DR
Recorded Rainfall	RR
Sustainable Development Goals	SDGs
Low Impact Development	LID
Società Metropolitana Acque Torino	SMAT
Digital Terrain Model	DTM
Open-Source Map	OSM
Curve Number	CN
Environmental Protection Agency	EPA
Integrated Management Practices	IMPs
Sustainable Urban Drainage Systems	SUDS
Stormwater Control Measures	SCMs
Litre Per Second	LPS
Water Elevation Profile	WEP
Hectares	ha
Square metre	M^2

Chapter 1.

Introduction

Introduction

The basis of this thesis is the internship that was done from April 2022 to December 2022 in the Metropolitan City of Turin and the Municipality of Venaria Reale. From the beginning, the decision had been made to recover the abandoned ancient channels to reduce surface flooding and runoff. These channels used to aim for irrigation, nowadays the usage of some of these channels is the same and the others have been entirely abandoned. For this thesis, the most pivotal sector of Venaria Reale (VR), specifically, the industrial segment (located in the southern part of VR), has been selected due to its history of significant flooding events. Throughout the internship, the primary objective encompassed understanding the existing state of VR to distinguish general challenges and formulate strategies to overcome these issues.

Moreover, rather than renovation of the abandoned channel, there was an effort to recognise the capabilities of the sewer system according to the two different precipitation data, known as Design Rainfall (DR) and Recorded Rainfall (RR), and if there would be a possibility of making a connection between the sewage system and the Druento channel to overcome of the main issue of VR. This effort involved integrating prior studies and projects, notably the unexecuted Life20 CCA(Commission 2019) initiative, with the United Nations' 2030 Agenda for Sustainable Development Goals (SDGs). This combination was driven by the appropriateness of objectives in specific articles within both frameworks, aimed at developing effective interventions within urban contexts and synchronising them with nature-based solutions, including implementing green infrastructure.

Over the course of the last few decades, intensified global urbanisation and urban flood catastrophes caused by unexpected significant rains as a result of climate change, have become an increasingly intense issue. To overcome these issues, there are several approaches such as sustainable urban drainage systems, water-sensitive urban design, low-impact urban design and development, and Low Impact Development (LID) to reduce the effects caused by flooding in different aspects of environmental, economic, social, and cultural impacts (Elliott and Trowsdale 2007), for this study, the main method focuses on LID practices.

Furthermore, analysing the application of green infrastructure and its efficiency in this region is twofold: **first**, the efficiency of green infrastructure, according to the quantity of decreasing surface runoff due to the application of Low Impact Development (LID) controllers, and **second,** investigating on the cost estimation to know what economic considerations contribute to the decision-making process in selecting these alternatives. It was required to analyse the case study VR to comprehend the location and its topography, including the amount of rainfall, soil type, flooding risk of VR, aquifer position to be refilled, and the number of canals that served as paths. In order to do these examinations, methodologically, the research employs two main software, Geographical Information System (GIS) and Storm Water Management Modelling (SWMM), which will be elaborated on in the relevant chapter, and subsequent chapters explain findings, propose strategies, and analyse the case study in three different scenarios.

By the conclusion of this thesis, it is anticipated to achieve the goals and targets of SDGs that held in common with life project, renovation of the ancient channel according to the nature-based solution, and a better understanding of sustainable urban water management, and its efficiency in the industrial sector of VR through the application of LID controllers with its financial effectiveness according to water discharge declines.

Chapter 2.

Data collection

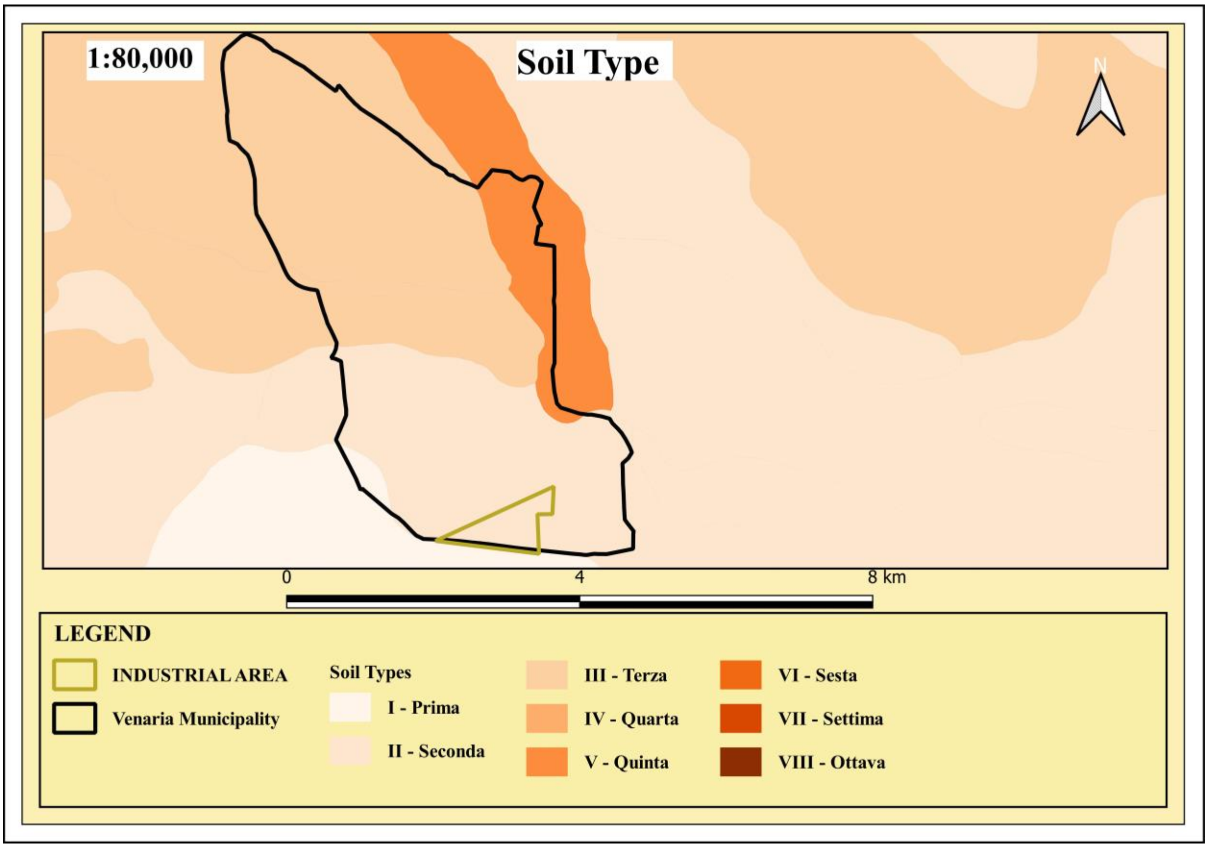
2.1. Data collection necessity

Based on the historical background of VR in significant flooding events, the reintegration of abandoned channels to mitigate surface discharge inflow of the urban area, the assessment of capabilities of the sewer system and the Druento channel is a necessity. On the other hand, a nature-based solution such as enhancing green infrastructures required intensive and systematic data collection for cost estimations in order to facilitate the future steps in the current study. Furthermore, the economic considerations for future decision-making made the data collection a curtail step as well.

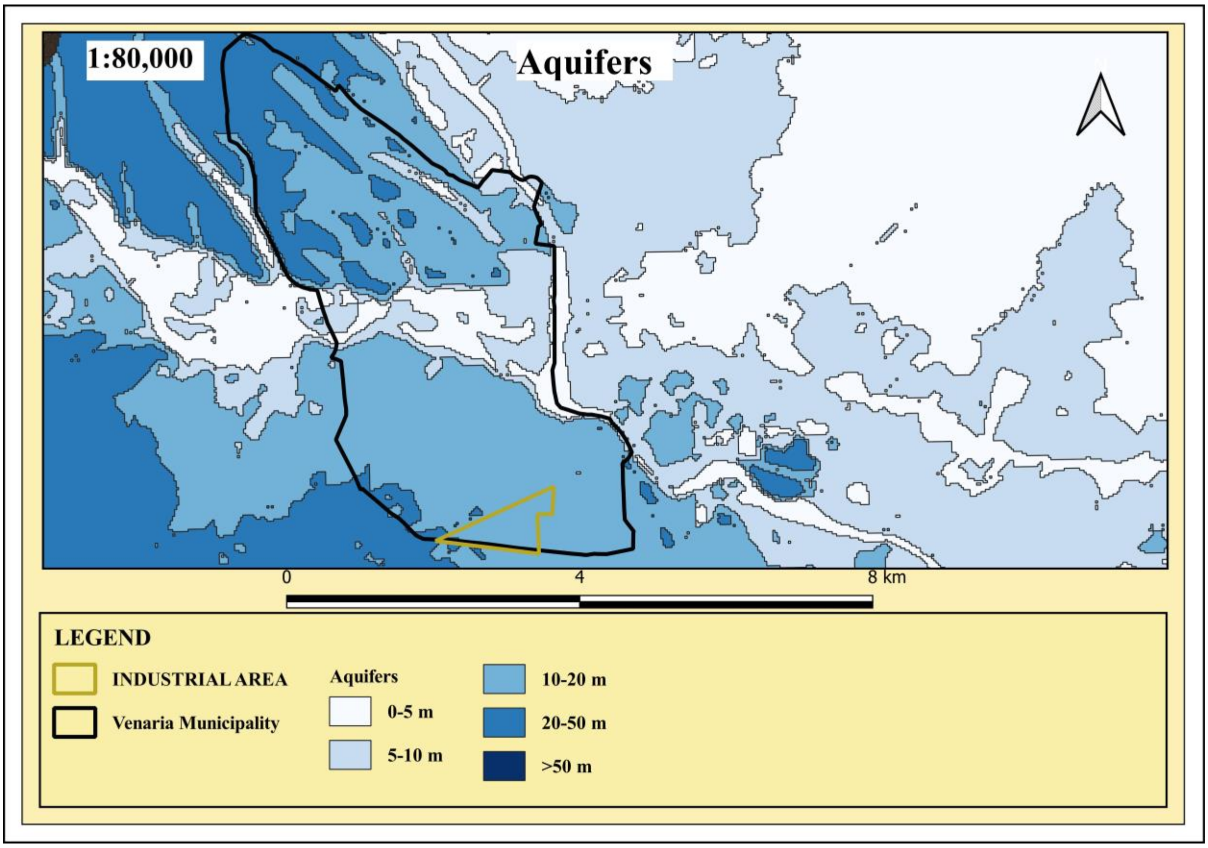
2.2. Geographic Information System

2.2.1. Feed data

As mentioned, GIS as a free and open-source geographic information system, was utilised to process the raw data obtained from the database of Metropolitan City of Turin and Geoportale Piemonte. Thus, topography (Digital Terrain Model -DTM), location, flooding risk of VR, hydraulic canals, soil type, and aquifer position (Figure (2.2.1.1)) were considered as the main data to be fed to GIS software with the aim of having curve number, accumulated water volume as well as the contour lines. Later on, the case study's map in .bmp picture format was developed.


1:80,000
Soil Type
N
0
4
8 km
LEGEND
INDUSTRIAL AREA
Venaria Municipality
Soil Types
I - Prima
II - Seconda
III - Terza
IV - Quarta
V - Quinta
VI - Sesta
VII - Settima
VIII - Ottava

(A)



(B)

Figure (2.2.1.1) Feed data on GIS; A) Aquifers, and B) Soil Type[1]

2.2.3. Output data

The main output data required for this investigation extracted from GIS software are watershed elevation, the case study's map in .bmp picture format, shapefiles, and contour lines. The processes of obtaining each of these parameters are explained in a sequential pattern. First, the location of VR on the satellite map (OSM) was determined and a series of .tiff format picture files from the region was generated. Later on, the case study's required data was extracted from the GIS software alongside cutting off a proper section from a wider map of the region. Next, the case study's geolocation definition was finalized by creating the vector file out of the raster file. Finally, the extracted DTM was fed to the Grass GIS software to obtain and extract the water accumulation volume, drainage pathways, basin locations, and stream pathways. The contour line, stylite maps, geological location and shapefile including

[1] https://geoportale.igr.piemonte.it/cms/

case study information were exploited to develop a final file comprising the required feed data for the post processes conducted via Storm Water Management Modelling (SWMM) software.

According to the Soil Conservation Services (SCS), ‘’determination of Curve Number (CN) depends on the watershed’s soil and cover conditions, which the model represents as hydrologic soil group, cover type, treatment, and hydrologic condition’’ as displayed in Table (2-1) (United States Department of Agriculture, June 1986).

Table 2-1. Base Curve Number data.

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

1. June 1986.Good cover is protected from grazing and litter and brush cover soil. Curve numbers are computed assuming that the runoff from the house and driveway is directed toward the street with a minimum of roof water directed to lawns where additional infiltration could occur. The remaining pervious areas (lawn) are considered to be in good pasture condition for these curve numbers. In some warmer climates of the country, a curve number of 95 may be used.

2.3. Storm Water Management Modelling

2.3.1. Feed data

The final file was exported from GIS and imported into the SWMM program to grasp the case study's present state and how to deal with and overcome to learn about the case study's current state and how to deal with and overcome the previously mentioned issue.

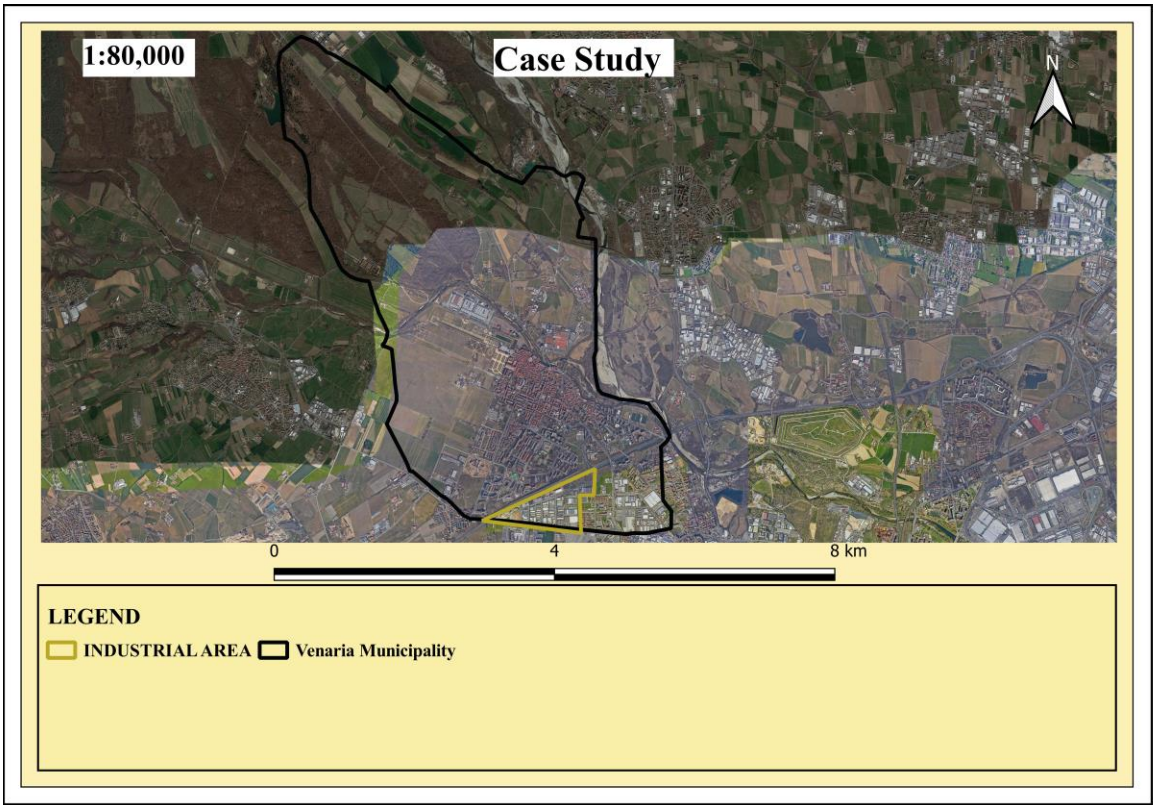


Figure 2-2-1 Geographical location of the case study.

Unfortunately, there was no available flooding map in the municipal archive. Therefore, the required data was acquired throughout one of the crucial rainfall times (November 21st to November 25th) in which they experienced floods inside the city (obtained from the **Arpa** website)[2]. It is noteworthy to mention that such data are known as Recorded Rainfall (RR). Moreover, other precipitation data including parameters of the rainfall probability indicator lines for return times of 20, 100, 200, and 500 years were utilized for future anticipation and decision-making processes. These data, which were defined as Design Rainfall (DR) data were attained from the **"AUTORITA 'DI BACINO DEL FIUME PO"** website[3].

In addition, the municipality of VR has detailed information on the abandoned channels in terms of dimensions, type, geometry, sizes, and the underground/above-ground sections, particularly in the industrial zones. Accordingly, these data were the main feed to the SWMM software to ultimately, develop the analyses concerning Vanaria's crucial rainfall time. Furthermore, the geometric information of the VR located in the industrial zone was provided by SMAT firm, which comprised the shape, size, elevation, and conduits loads. The canals' structural models were later developed again via SWMM software to earn the most realistic and accurate data.

2.3.2. Output data

The main outputs extracted from this software were different scenarios that were defined based on involving regional components of green roofs, permeable pavements, and rain gardens. Moreover, capital cost estimations were also calculated employing SWMM software considering 15% of general expenses and 22% of Italian taxes (VAT).

[2] https://www.arpa.piemonte.it/

[3] https://www.adbpo.it/

Chapter 3.

Methodology

3.1. Introduction

This chapter underlines and describes the methods employed in this research, outlining the steps taken to address the research question. After attaining the raw data, as stated in the previous chapter, numerous post-processing was crucial to address the main issues of VR. The main objective is primarily to evaluate the possibility of reclaiming and reusing the abandoned channel to handle surface runoff in the urban area in an optimized order. Later on, the capabilities of the sewage network and Druento channel as well as incorporating a nature-based solution into them were studied. The effectiveness of employing green infrastructures was also investigated followed by the estimation of capital cost through the economic point of view.

This research utilized a mixed method, combining observational, data analysis, and quantitative surveys regarding the case study to understand the main problematic issues and figure out how to overcome them. GIS and SWMM software were exploited to provide valuable insights into their functionalities, features, and potential applications in different scenarios. According to the obtained information, the decision was made to analyse the case study in three possible scenarios to carry out a comprehensive investigation of the case study and address the issues using the best qualitative solutions. Figure (3-1) shows the research plan in a flowchart.

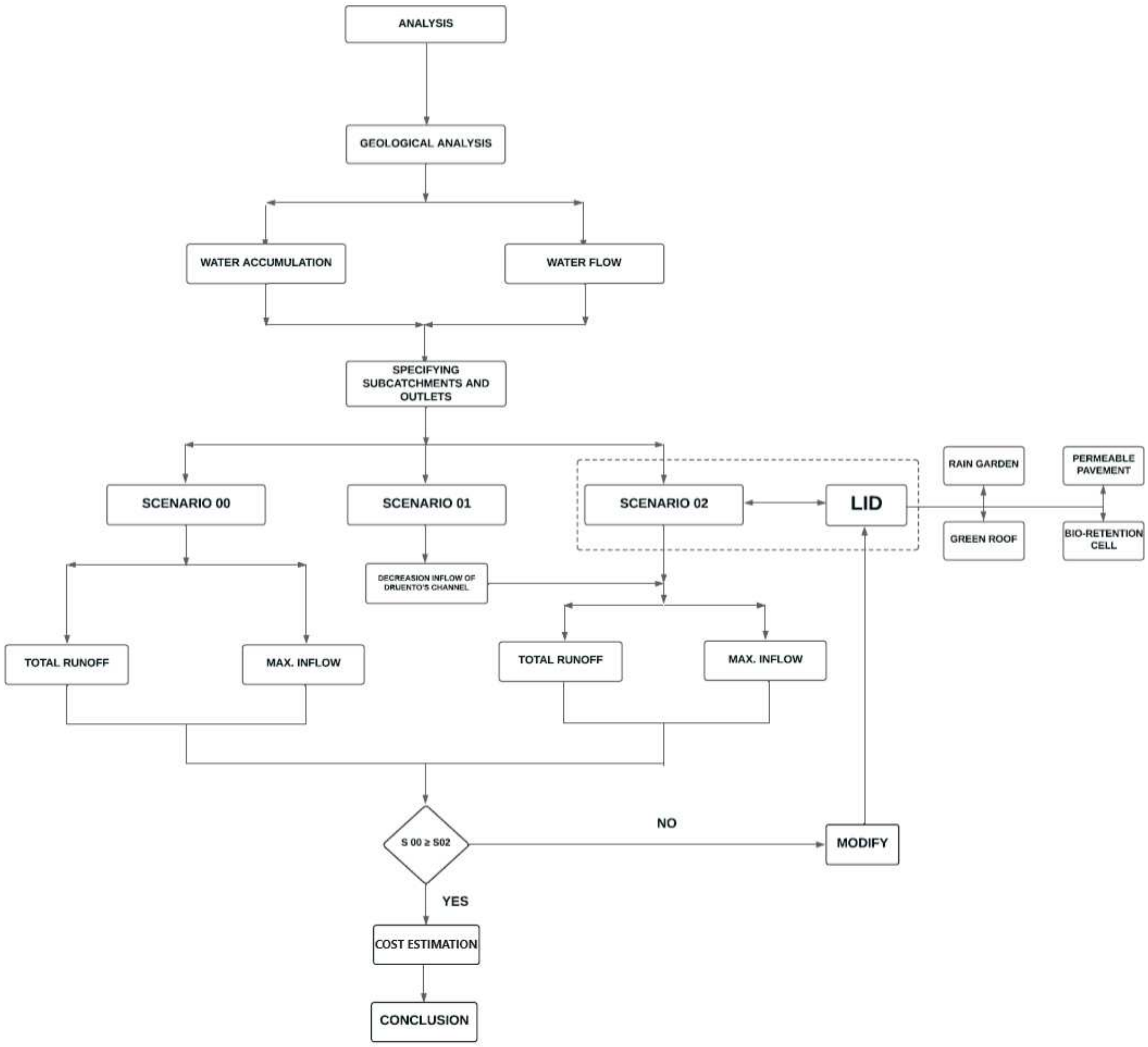


Figure (3-1). Research process flowchart.

The UN Sustainable Development Goals were adopted in 2016, formalising the most challenging issues on the way of sustainable development that decision-makers may face globally (Ilse M. Voskamp, 2021). Both the New Urban Agenda, which seeks to expedite its realisation, and any specific urban goal embedded in the UN Sustainable Development Goals (N.6, 11, 13, 15, and 17), provide a vivid view explaining how critical role the cities can play in local and global sustainable development (Nations, 2017). Table (3-1) shows the UN Sustainable Development Goals and targets.

Table 3-1. UN Sustainable Development Goals and Targets (Nations, 2017).

Goals	Symbol	Targets	Description
CLEAN WATER AND SANITATION		Target 6.5	‘’Implement integrated water resources management at all levels, including through transboundary cooperation as appropriate, to support the achievement of sustainable development goals related to water and sanitation’’.
		Target 6.6	‘’Protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers, and lakes’’.
SUSTAINABLE CITIES AND COMUNITIES		Target 11.5	‘’Significantly reduce the number of deaths and the number of people affected and substantially **decrease the direct economic losses relative to the global gross domestic product caused by disasters**, including water-related disasters, focusing on protecting the poor and people in vulnerable situations’’.
		Target 11. b	‘’Substantially increase the number of cities and human settlements adopting and implementing integrated policies and plans towards inclusion, resource efficiency, **mitigation and adaptation to climate change,** resilience to disasters, and develop and implement, in line with the Sendai Framework for Disaster Risk Reduction 2015-2030, holistic disaster risk management at all levels’’.
CLIMATE ACTION		Target 13.1	‘’Strengthen resilience and adaptive capacity to all countries' **climate-related hazards and natural disasters’’.**
		Target 13.2	‘’Integrate climate change measures into national policies, strategies, and planning’’.
LIFE ON LAND		Target 15.1	‘’Ensure the **conservation, restoration, and sustainable use of terrestrial and inland freshwater ecosystems and their services**, in particular, forests, **wetlands**, mountains, and drylands, in line with obligations under international agreements’’.
PARTNERSHIPS FOR THE GOALS		Target 17.6	‘’Enhance North-South, South-South, and triangular regional and international cooperation on and access to science, technology, and innovation and enhance knowledge-sharing on mutually agreed terms, including through improved coordination among existing mechanisms, particularly at the United Nations level, and through global technology facilitation mechanism.’’

3.2. Definitions

At this point in the dissertation, it is appropriate to introduce some definitions in order to understand the concept and how to achieve the aims.

‘’The Environmental Protection Agency (**EPA**) Storm Water Management Model (**SWMM**) is a dynamic rainfall-runoff simulation model used for a single event or long-term (continuous) simulation of runoff quantity and quality from primarily urban areas. The runoff component of SWMM operates on a collection of sub-catchment areas that receive precipitation and generate runoff and pollutant loads. The routing portion of SWMM transports this runoff through a system of pipes, channels, storage/treatment devices, pumps, and regulators. SWMM tracks the quantity and quality of runoff generated within each sub-catchment, and the flow rate, flow depth, and quality of water in each pipe and channel during a simulation period comprised of multiple time steps. SWMM was first developed in 1971 and has undergone several major upgrades since then. It continues to be widely used throughout the world for planning, analysis and design related to stormwater runoff, combined sewers, sanitary sewers, and other drainage systems in urban areas, with many applications in non-urban areas as well.

Sub-catchments are hydrologic units of land whose topography and drainage system elements direct surface runoff to a single discharge point. Sub-catchments are divided into pervious and impervious subareas. Surface runoff can infiltrate into the upper soil zone of the pervious subarea, but not through the impervious subarea. Impervious areas are themselves divided into two subareas - one that contains depression storage and another that does not. Runoff flow from one subarea in a sub-catchment can be routed to the other subarea, or both subareas can drain to the sub-catchment outlet.

A network of natural and semi-natural environments (green roof, bio-retention cell, permeable pavement, bioswale, and rain garden), such as green spaces, blue spaces, and other ecosystems, that have been carefully planned and managed to provide a variety of ecosystem services across multiple dimensions is known as ‘’**Green Infrastructure**’’ (Monteiro R, 16 December 2020). **Low Impact Development (LID)** controls are landscaping practices designed to capture and retain stormwater generated from impervious surfaces that would otherwise run off of a site. They are also referred to as green infrastructure (GI), Integrated Management Practices (IMPs), Sustainable Urban Drainage Systems (SUDS), and Stormwater Control Measures (SCMs)”[4].

According to the Soil Conservation Services (SCS), ‘’determination of **Curve Number** (CN) depends on the watershed’s soil and cover conditions, which the model represents as

[4] https://www.epa.gov/water-research/storm-water-management-model-swmm

hydrologic soil group, cover type, treatment, and hydrologic condition'' (United States Department of Agriculture, June 1986).

Table 3-2. Definition of Green Infrastructure as LID Controllers[5]

LID Controllers	definition	Berm height (mm)	Soil thickness (mm)	Storage thickness (mm)	Pavement thickness (mm)
Green Roof (GR)	''A variation of bioretention cells that have a soil layer atop a special drainage mat material that conveys excess percolated rainfall off of the roof. They contain vegetation that enables rainfall infiltration and evapotranspiration of stored water''.	100	400	*	*
Rain Garden (RG)	''Depressed areas, planted with grasses, flowers, and other plants, collect rainwater from a roof, driveway, or street and allow it to infiltrate into the ground. More complex rain gardens are often referred to as bioretention cells''.	300	400	*	*
Bioretention Cells (or Bioswales)	''Depressions containing vegetation grown in an engineered soil mixture placed above a gravel drainage bed that provides storage, infiltration, and evaporation of both direct rainfall and runoff captured from surrounding areas''.	400	400	500	*
Permeable pavement (PP)	''Allows rainfall to immediately pass through the pavement into the gravel storage layer below where it can infiltrate at natural rates into the site's native soil. In block paver systems, rainfall is captured in the open spaces between the blocks and conveyed to the storage zone and native soil below''.	*	100	100	100

3.3. Methodology structure

Climate change effects and the growth of urbanization have led to a substantial increase in impervious surfaces, consequently, tending to significant levels of stormwater runoff, flood risks, overflowing sewer systems, and stormwater infrastructure deterioration (Niki Frantzeskaki, 2016). Recently, LID became known as a popular method for minimising flood risk and controlling stormwater (Fletcher, et al., 2015) via the employing green roofs, rain gardens, bio-retention cells, and permeable pavement (Zhang, et al., 2021).

According to the research plan flowchart shown in Figure (3-1), in order to measure flooding, and evaluate the effectiveness of the stormwater drainage system located in VR, a simulation study was performed. The main purpose of utilising SWMM software is to locate flood regions, simulate surface runoffs' quantity and/or quality from mostly urban

[5] https://www.epa.gov/water-research/storm-water-management-model-swmm

watersheds, assess various stormwater management techniques, and develop economical and adaptable stormwater control solutions (Salam Naje Hussaina, 2022).

The developed alternatives to address the mentioned challenges of VR are divided into three options and each of them is named Scenario. After redeveloping the region's geographical characterisation, in the first Scenario (Scenario_00), the case study partitioned 82.29 hectares (the total area of the case study) into 18 sub-catchments in order to conduct further analysis. Moreover, the entire sewer system of the VR's industrial zone and the abandoned channel known as Druento, were internally and externally connected via 129 nodes, 129 conduits, and 3 outfalls. As outlined before, the redrawn model is constructed in real-size dimensions exploiting the acquired data from this study's partners. The main purpose of this scenario is to realize the total runoff and maximum inflow of VR considering 2 sets of different precipitation data, DR, and RR.

In the second Scenario (Scenaario_01), besides the aims outlined for the first Scenario, an extra effort was made to investigate the effects of changing the Druento channel's characteristics as well as the creation of new water pathways from the sewer network to this abandoned channel. It was conducted hoping that the risk of total runoff is reduced in each sub-catchment considerably if not totally, and the flood risk in the VR is mitigated.

In the last Scenario (Scenario_02), the analysis was conducted in the eastern section of the case study (figure 4), due to the application of LID controllers and their efficiency in both total runoff reduction and economical solution. The sub-catchments water inflow of this scenario should be compared with Scenario_00 and Scenario_01, if the sub-catchments total runoff is equal to or less than the other Scenarios, it means that they are efficient in reducing and mitigating surface runoff, otherwise, there is a need for modification for redesigning LID controllers. Notably, the study section is divided into public and private sectors (figure 5) due to the functionality of this region to make a decision on the type of intervention according to the available regulatory framework. Furthermore, before concluding, a cost analysis of LID controllers should be conducted to find out the most efficient alternative by considering cost estimation and surface runoff mitigation.

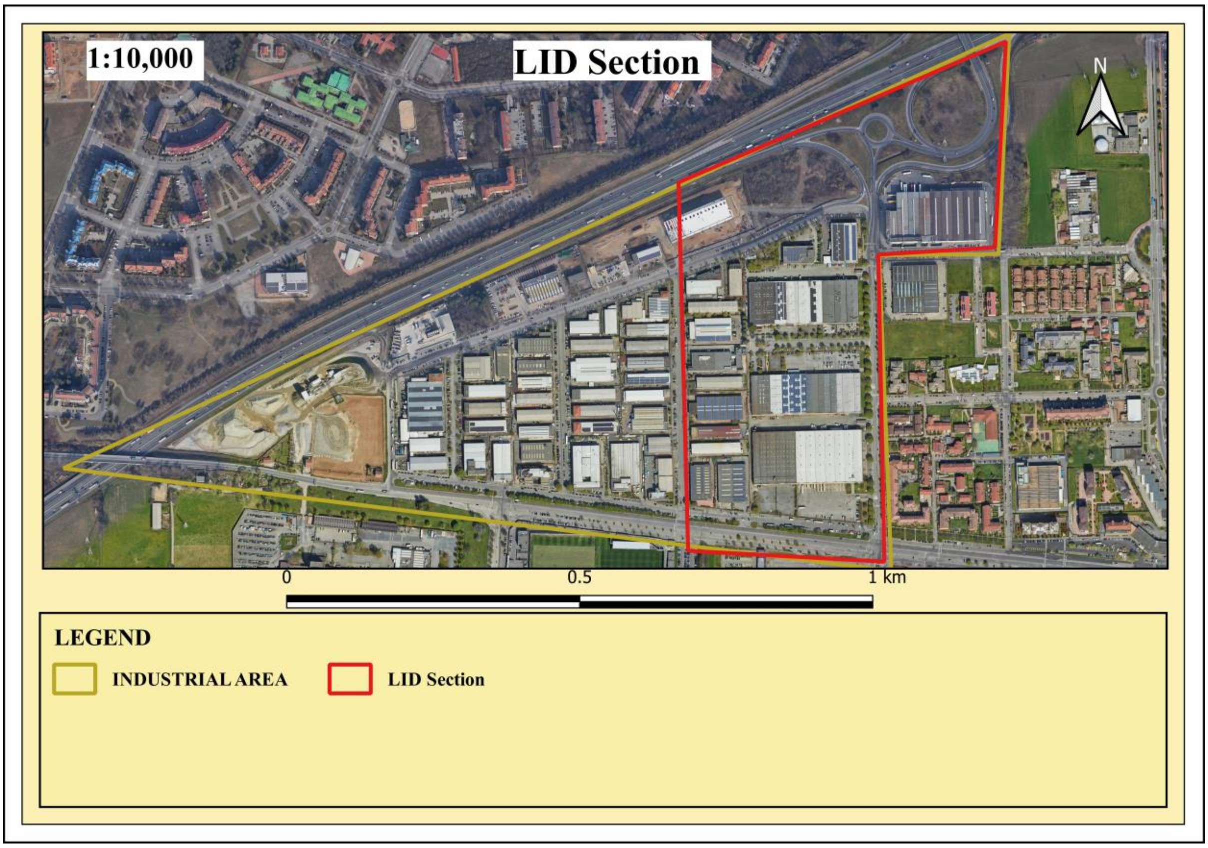


Figure (3-2). The Low Impact Development section of the VR

Chapter 4.

Results

4.1. Introduction

In this chapter, the obtained data from the utilised software (GIS and SWMM) are presented in detail. The resulted outcomes from GIS include accumulated water volume and CN that were calculated based on DTM, location, soil type, flooding risk of VR, hydraulic canals, and aquifer position information. Moreover, the SWMM was fed by the calculated data by GIS. As a result, three different scenarios were defined to evaluate the possible alternatives via SWMM software to address the surface runoffs in VR named Scenario_00, Scenario_01, and Scenario_02. Moreover, a detailed comprehension of each defined scenario, including the utilised approaches, results, as well as particular factors influencing the interventions resulted from LID practices was provided.

4.2. GIS output data

4.2.1. Accumulated water volume

The Accumulated water volume of the studied region extracted from GIS is shown in Figure (4-1).

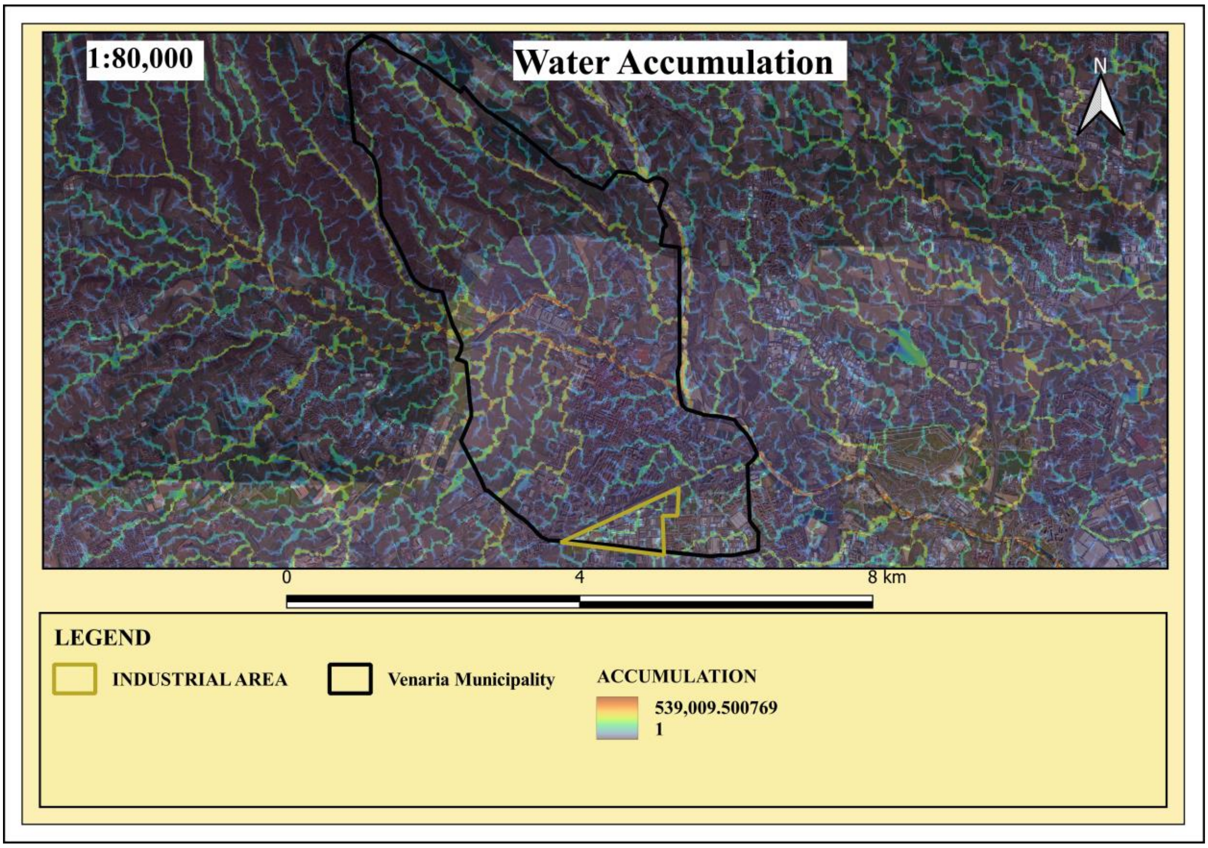


Figure (4-1). Water accumulation of Venaria Reale.

As depicted, it is evident that the water pathway from the northern part of the VR is a natural pathway stretched from the upstream to the downstream that ends up in the Stura di Lorenzo River. The natural movement of the water inside the urbanised area, speciality in the industrial zone, has been interrupted as a result of new constructions and developments. In other words, the movement direction of the water has not changed completely, and it finally ends up in the river, although several barriers are in its way and the velocity of the water has dramatically declined.

4.2.2. Curve number (CN)

The CN data extracted from GIS software are shown in Figure (4-2). As outlined before, these were developed using base curve number data. As a result, the map related to the case study was prepared and validated with an available CN map provided before(Pastorello 2018/2019). In fact, a slight variation was found due to the fact that the analysis of current research, which was more accurate, is focused on a more specific and limited/smaller area compared to that of Pastorello, et.al.

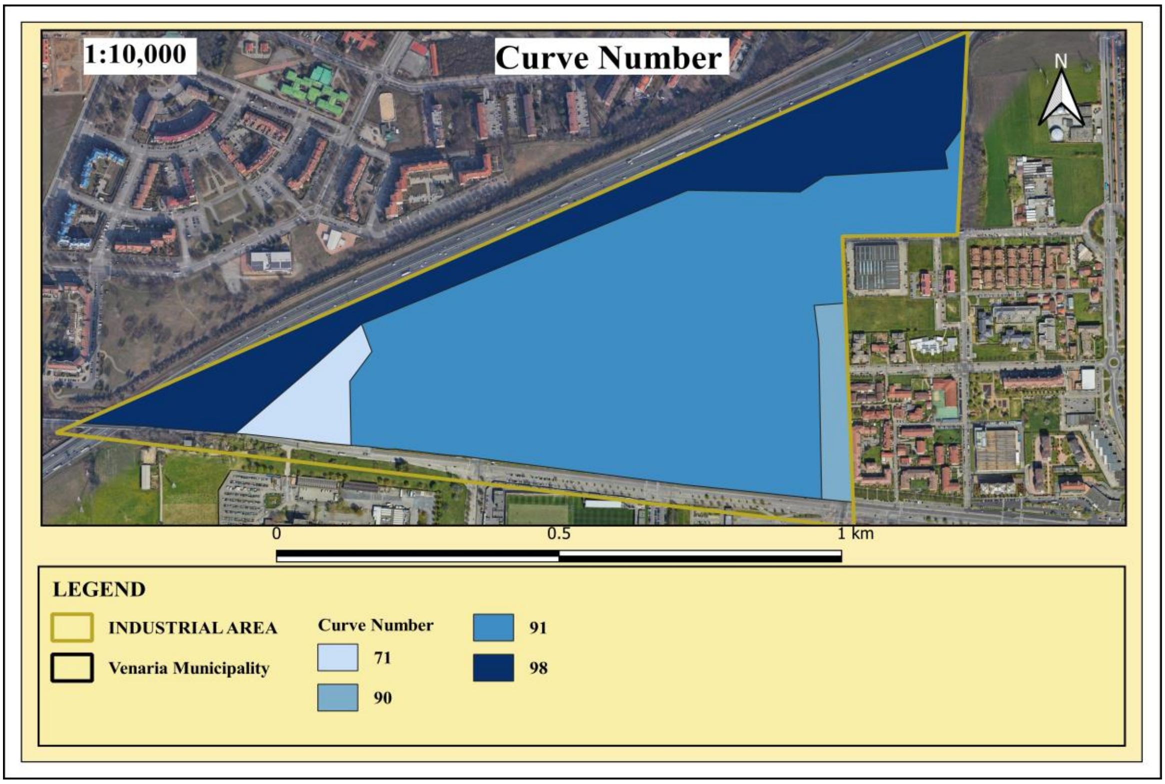


Figure (4-2). Curve Number (CN) map.

4.3. SWMM Output data

4.3.1. Scenario_00

In this scenario, as discussed earlier, a detailed analysis has been conducted on the existing sewer system and the abandoned Druento channel using two different precipitation schemas to provide vivid insights into the challenges and vulnerabilities present in the current step. In other words, RR and DR data were considered as two sets of input data to evaluate the precipitation, runoff, and flooding in the region based on the objectives of the different scenarios. Figure 4-3, illustrates the 3D model of the case study exported from SketchUp software to have an overview of the section.

Figure (4-3). 3D model of the case study.

4.3.1.1. Design Rainfall.

To better understand this section, there should be an introduction to each section of the SWMM software. Figure (4-4) illustrates the volume of the entire system's precipitation, runoff, and flooding during 24 hours of precipitation. As expected, the critical hour of the analysis was 8:00 a.m., representing not only the maximum volume of the precipitation but also the peak runoff and system flooding. It should be noticed that from a considerable point of view, the system flooding after 20 hours that rainfall was finished, is still steady and it does not absorb nor conduct water to another place.

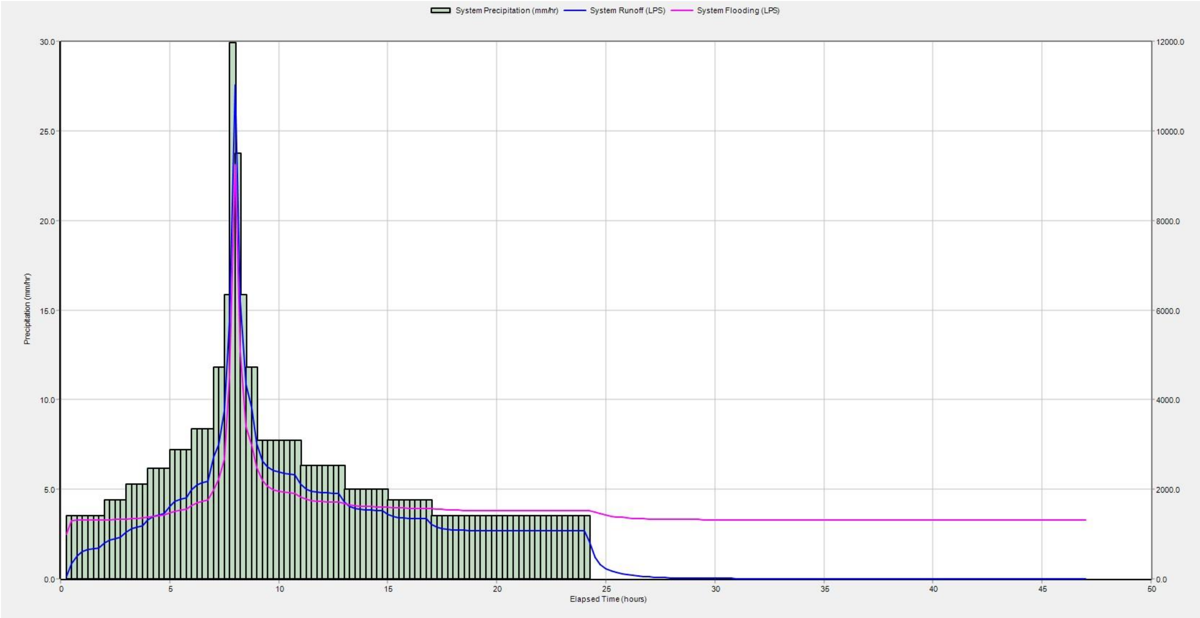


Figure (4-4). System precipitation, runoff, and flooding based on DR data.

Figure (4-5) depicts the sub-catchments of the Venaria before the precipitation starts. In this section, the sub-catchment runoff, the nodes' flooding, and the links' capacity (conduits and Druento's channel) were considered for the measurements. Notably, the quantity of 500 litres per second has been considered in Druento's channel according to the presence of the irrigation water inside to get the best result from the simulation. Hence, some parts of the channel were exhibited in different colours. The considered measurement for the links shows the capacity of the conduits and channels.

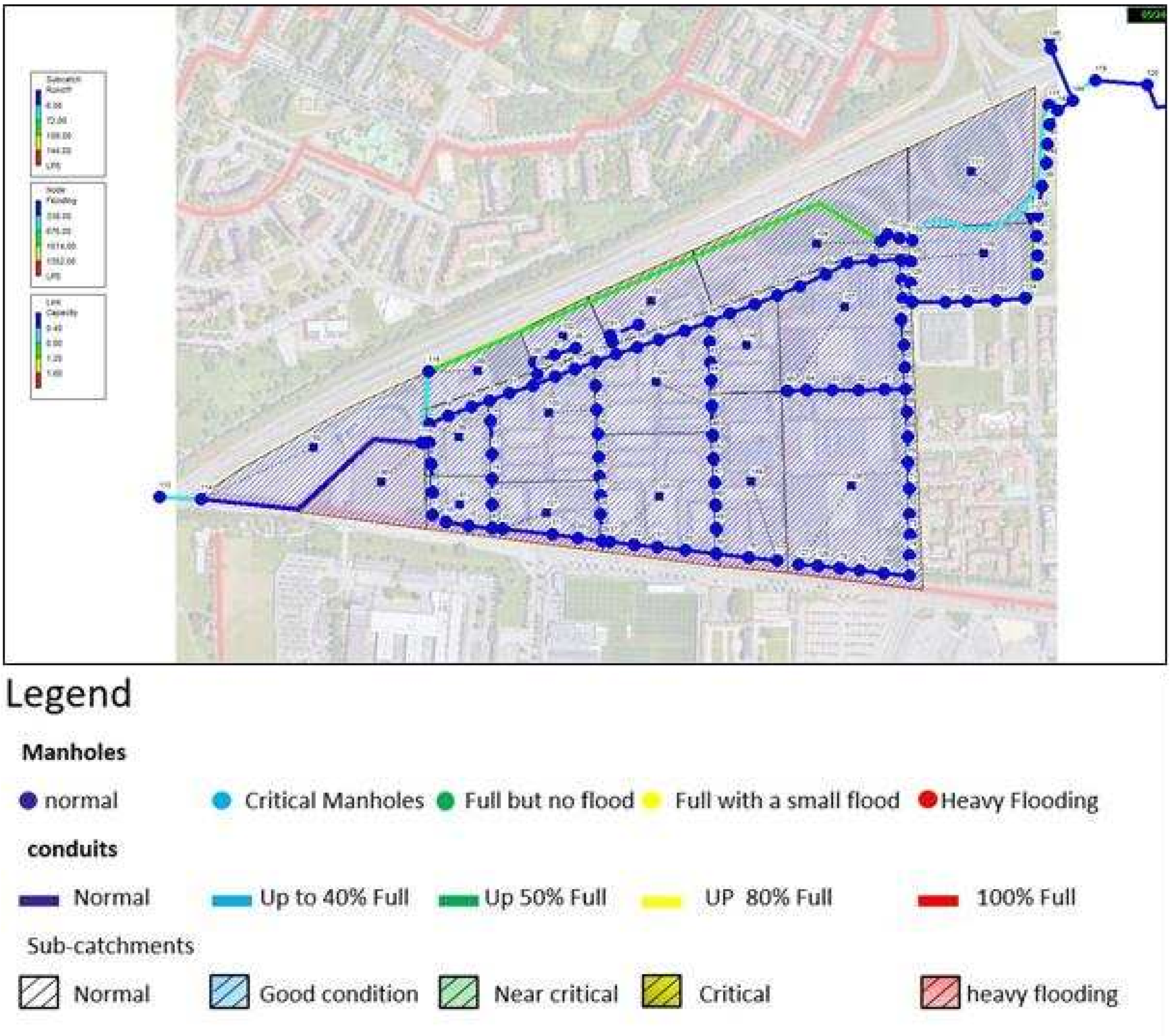


Figure (4-5). Sub-catchments before precipitation

Table (4-1) provides information on the maximum load of the available outfalls in the industrial area of Venaria Reale. This information makes it understandable how much the load of the exiting point of water (LPS) is.

Table (4-1). Outfall loading

Outfall Node	Flow Freq. Pcnt.	Avg. Flow LPS	Max. Flow LPS	Total Volume 10^6 ltr
112	98.38	50.94	367.94	8.456
146	99.94	1393.33	3157.54	235.156
147	99.84	1084.73	1088.19	182.743

Table (4-2) provides information on the peak runoff and discharge of each sub-catchment separately due to the total precipitation of 146.72 mm. Noteworthy, sub-catchment 106 exhibits the highest peak runoff at 1650.54 LPS.

Table (4-2). Sub-catchment details

Subcatchment	Total Precip mm	Total Runon mm	Total Evap mm	Total Infil mm	Imperv Runoff mm	Perv Runoff mm	Total Runoff mm	Total Runoff 10^6 ltr	Peak Runoff LPS	Runoff Coeff
93	146.72	0.00	0.00	28.55	0.00	117.95	117.95	8.53	408.35	0.804
96	146.72	0.00	0.00	42.94	0.00	103.65	103.65	4.53	238.39	0.706
97	146.72	0.00	0.00	2.88	124.75	19.13	143.88	3.29	295.52	0.981
98	146.72	0.00	0.00	2.88	124.74	19.13	143.87	4.47	397.23	0.981
99	146.72	0.00	0.00	42.67	0.00	103.98	103.98	2.64	165.00	0.709
100	146.72	0.00	0.00	2.88	124.72	19.12	143.84	10.46	871.32	0.980
101	146.72	0.00	0.00	2.88	124.74	19.13	143.86	5.87	513.90	0.981
102	146.72	0.00	0.00	2.88	124.75	19.13	143.88	3.24	290.49	0.981
103	146.72	0.00	0.00	2.88	124.74	19.13	143.86	5.73	502.05	0.981
104	146.72	0.00	0.00	2.88	124.72	19.12	143.84	10.59	880.87	0.980
105	146.72	0.00	0.00	2.88	124.72	19.12	143.83	12.77	1038.36	0.980
106	146.72	0.00	0.00	2.89	124.70	19.11	143.81	22.22	1650.54	0.980
107	146.72	0.00	0.00	2.88	124.71	19.12	143.83	14.67	1169.63	0.980
108	146.72	0.00	0.00	7.87	105.66	33.20	138.86	7.75	649.37	0.946
109	146.72	0.00	0.00	66.33	0.00	80.11	80.11	7.99	282.81	0.546
111	146.72	0.00	0.00	43.48	0.00	102.99	102.99	8.46	367.94	0.702
148	146.72	0.00	0.00	2.88	124.74	19.13	143.86	5.44	478.23	0.981
149	146.72	0.00	0.00	2.88	124.72	19.12	143.84	10.36	863.87	0.980

The analysis illustrates that the critical moment after the precipitation begins at 7:45 a.m. (Figure 4-6). The majority of the sub-catchments are experiencing a surface flood except the those with yellow and green colours. The nodes that show the manholes, illustrate that they experience their maximum capacity (showed light blue) and one of them starts flooding (node 120) from the first hour of the rainfall. The current conduits and channel are still in good condition and do not experience flooding.

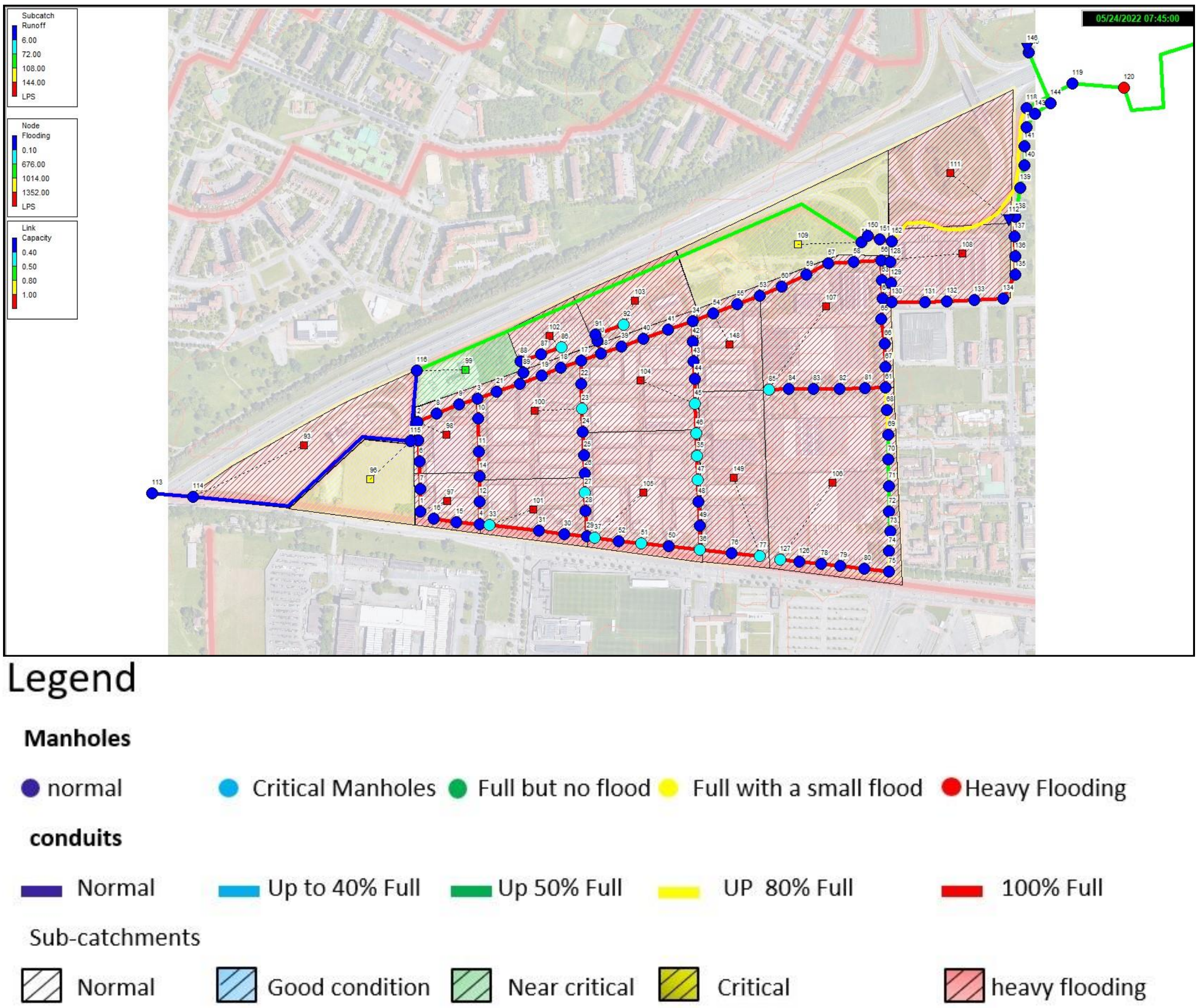
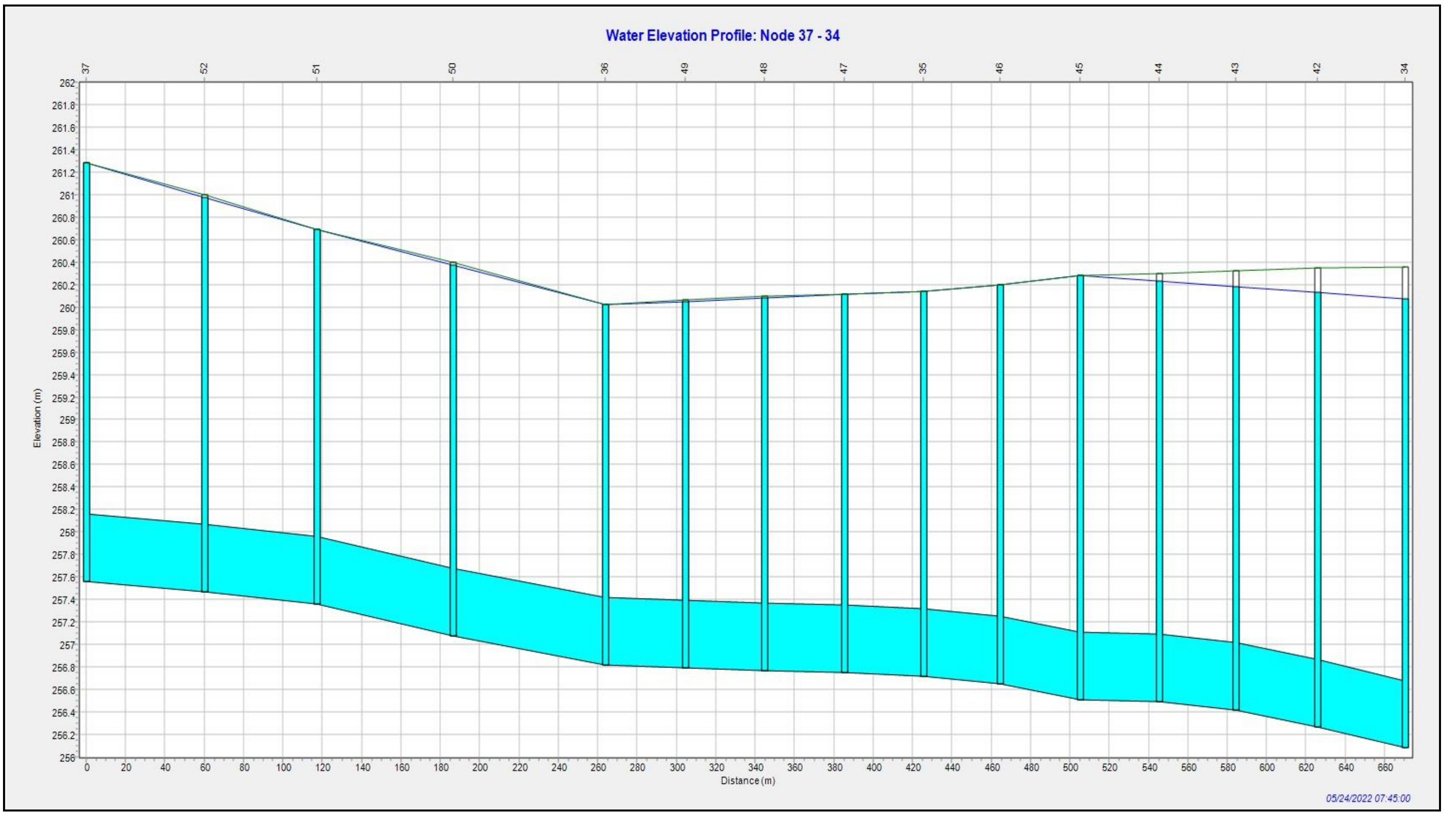
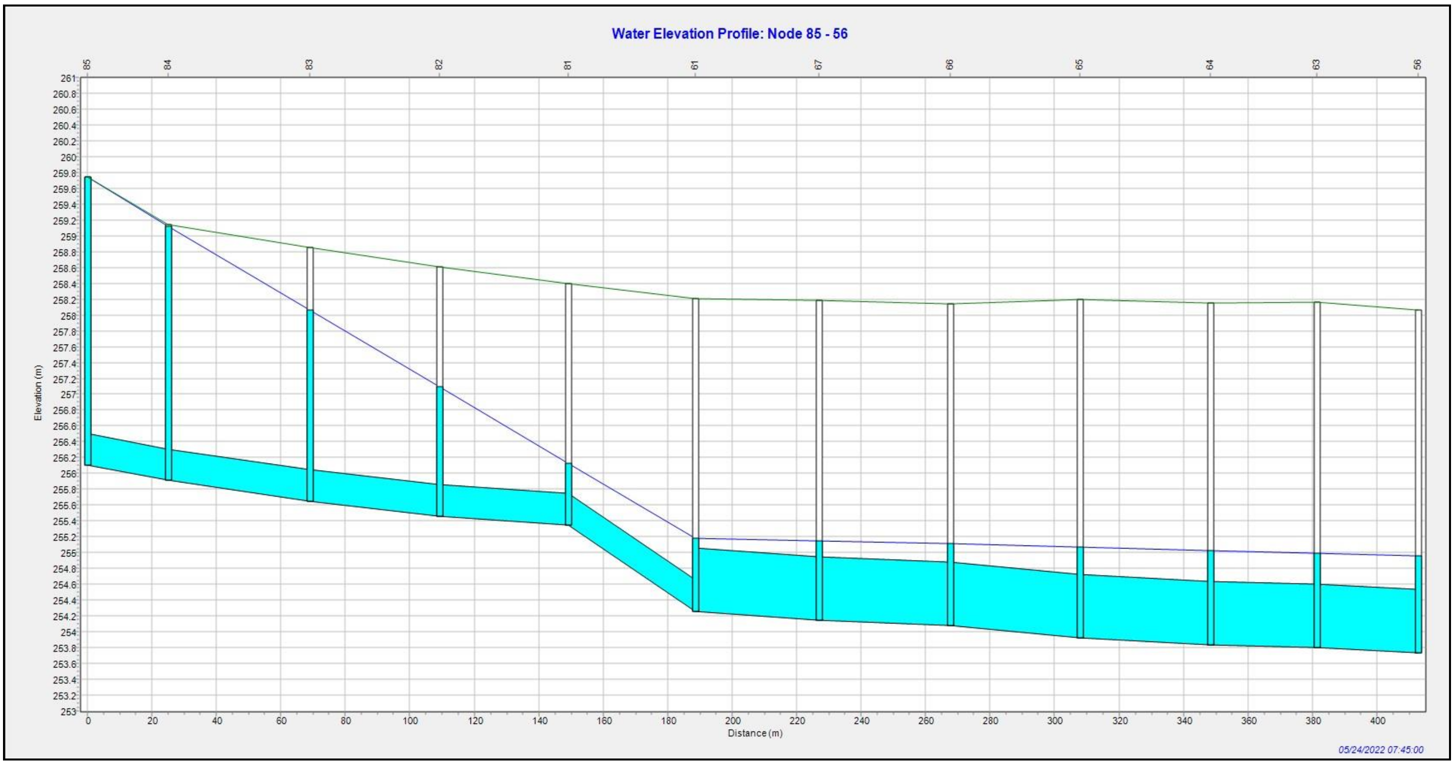


Figure (4-6). Sub-catchments at 7:45 a.m.

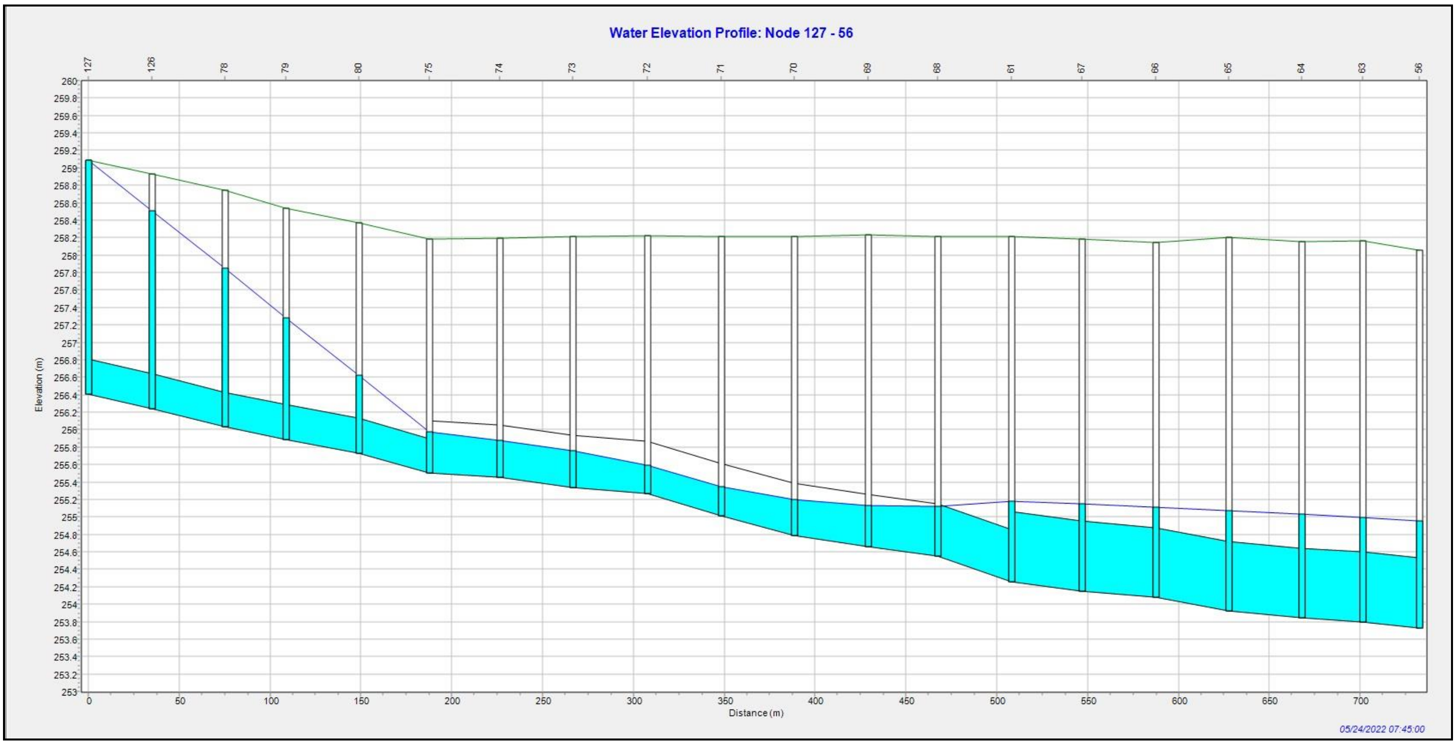
Figure (4-7) suggests the critical manholes and conduits where flooding was observed, known as water elevation profiles (WEP).


Water Elevation Profile: Node 37 - 34
37 52 51 50 36 49 48 47 35 46 45 44 43 42 34
Elevation (m)
Distance (m)
05/24/2022 07:45:00

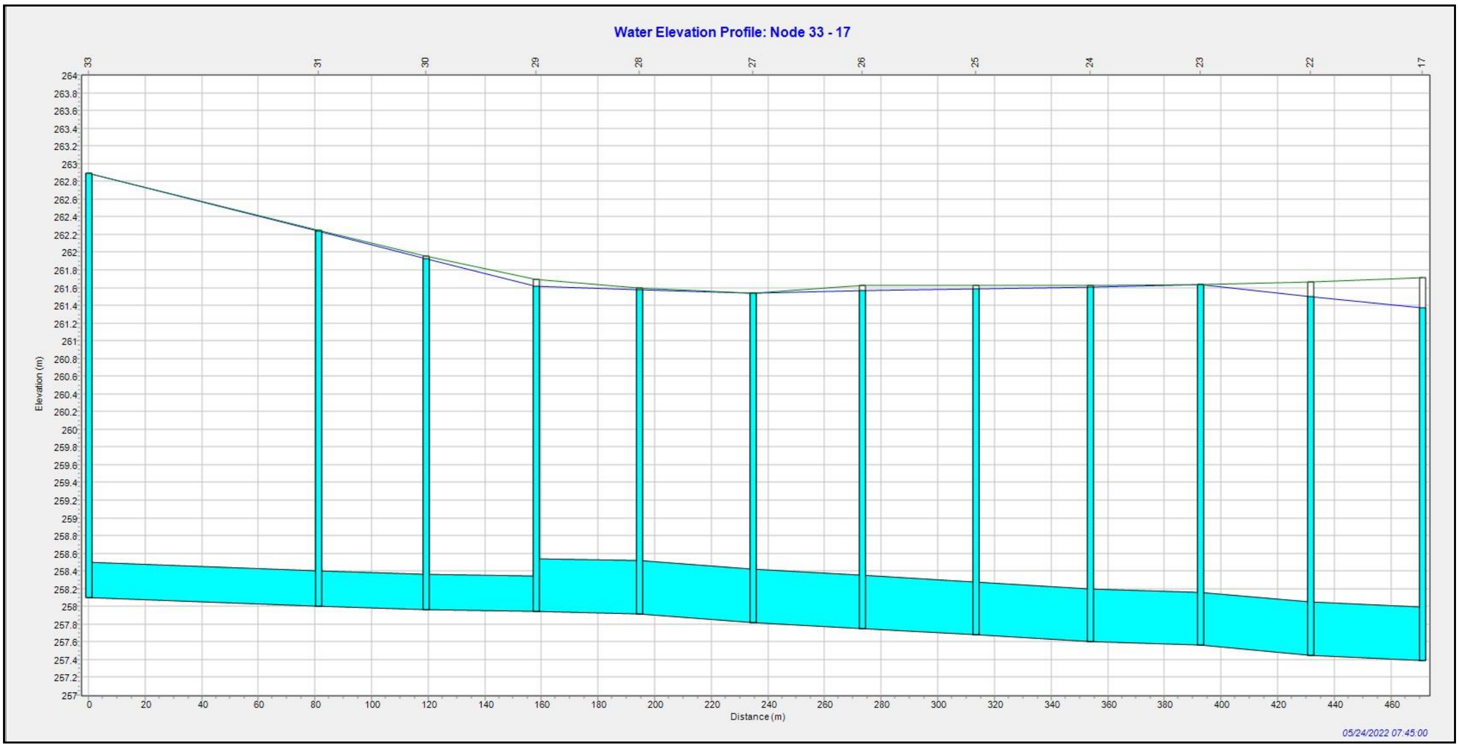
(A)


Water Elevation Profile: Node 85 - 56
85 84 83 82 81 61 67 66 65 64 63 56
Elevation (m)
Distance (m)
05/24/2022 07:45:00

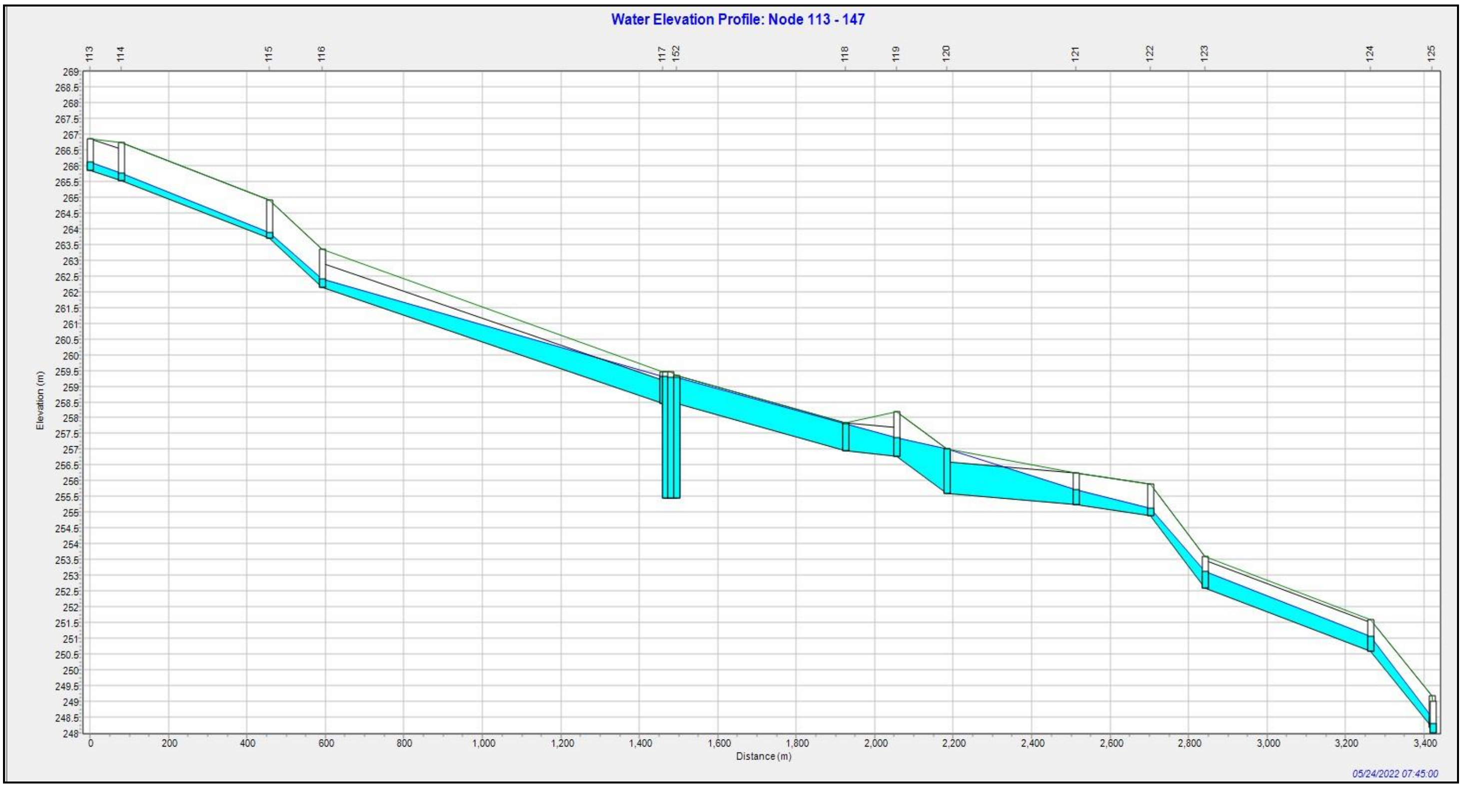
(B)


Water Elevation Profile: Node 127 - 56
127 126 78 79 80 75 74 73 72 71 70 69 68 61 67 66 65 64 63 56
Elevation (m)
Distance (m)
05/24/2022 07:45:00

(C)


Water Elevation Profile: Node 33 - 17
33 31 30 29 28 27 26 25 24 23 22 17
Elevation (m)
Distance (m)
05/24/2022 07:45:00

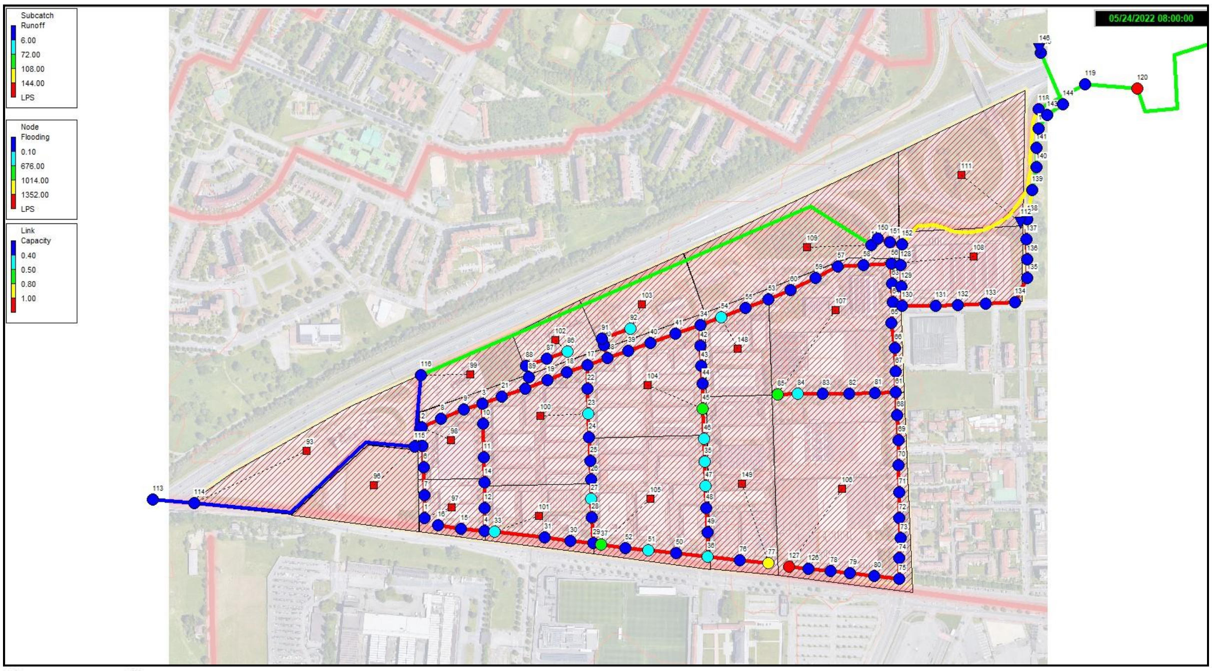
(D)



(E)

Figure (4-7). Water elevation profiles at 7.45 am A) WEP 27_34; B) WEP 85_56; C) WEP 127_56; D) WEP 33_17; E) WEP of Druento.

Figure (4-8) demonstrates an overview of all the sub-catchments where the precipitation and flooding happened. The most critical time for the flooding of the nodes demonstrates flooding in manhole numbers 120, and 127. Additionally, the other manholes such as 77, 33, 37, 23, 45, and 85 are in a critical situation and are going to pass their maximum range of capacity within the sewer system (Figure 4-9).



Legend

Manholes

normal | Critical Manholes | Full but no flood | Full with a small flood | Heavy Flooding

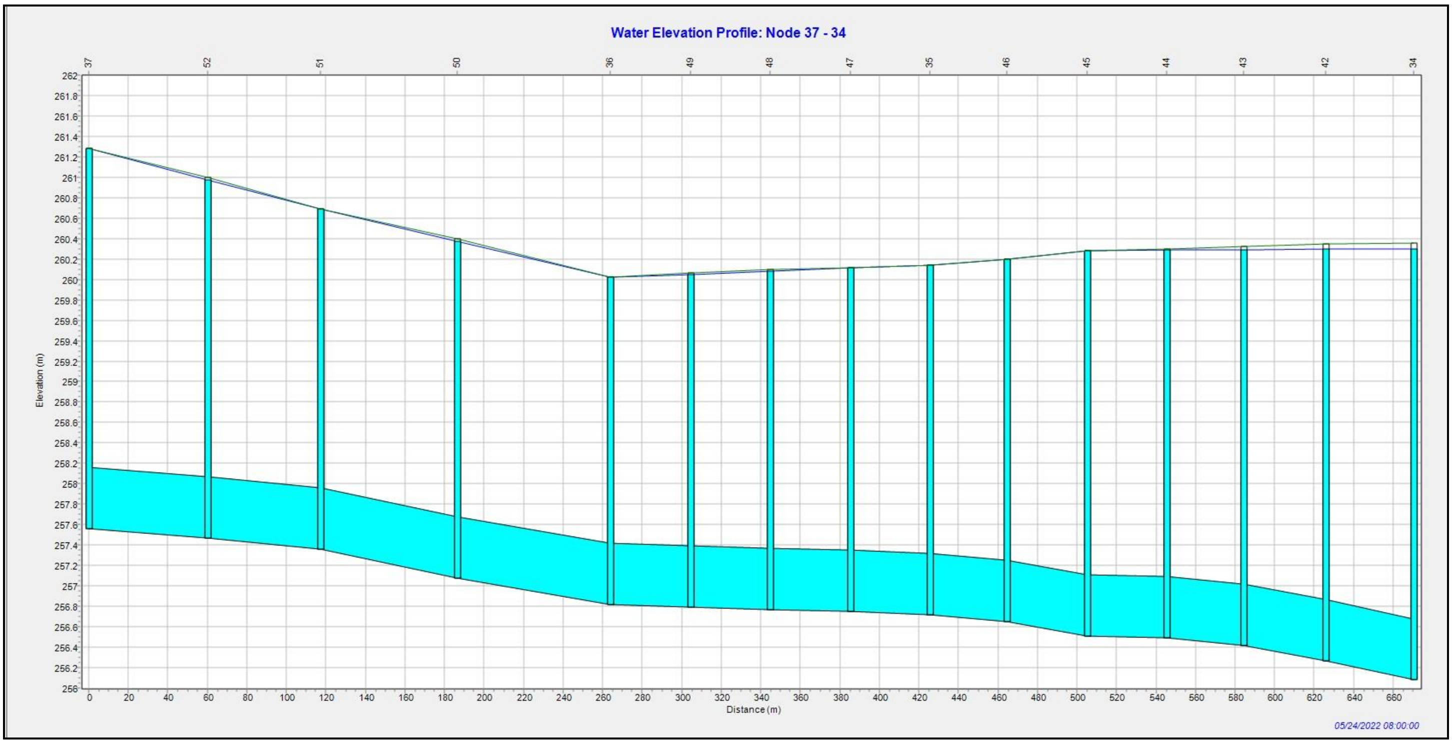
conduits

Normal | Up to 40% Full | Up 50% Full | UP 80% Full | 100% Full

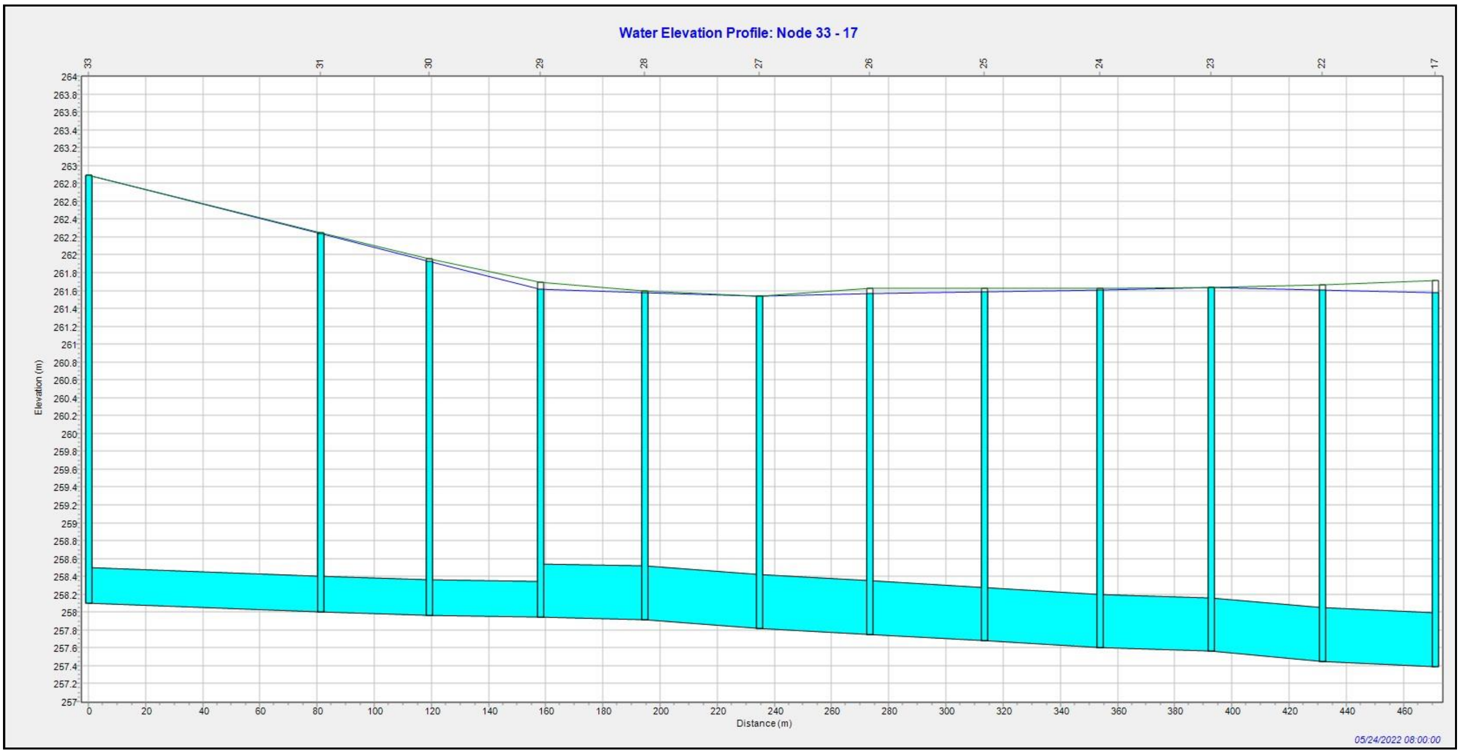
Sub-catchments

Normal | Good condition | Near critical | Critical | heavy flooding

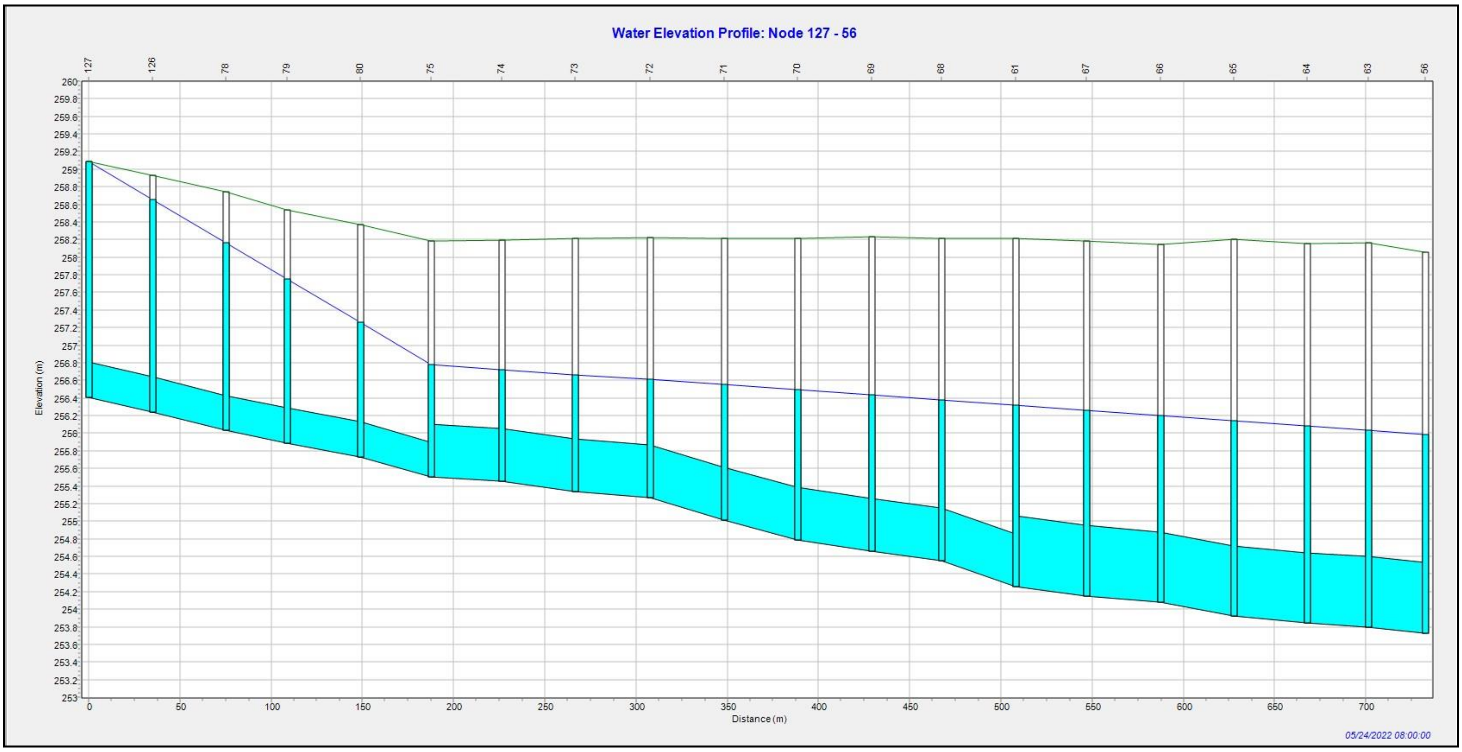
Figure (4-8). Sub-catchments at 8.00 a.m.


Water Elevation Profile: Node 37 - 34
Elevation (m)
Distance (m)
05/24/2022 08:00:00

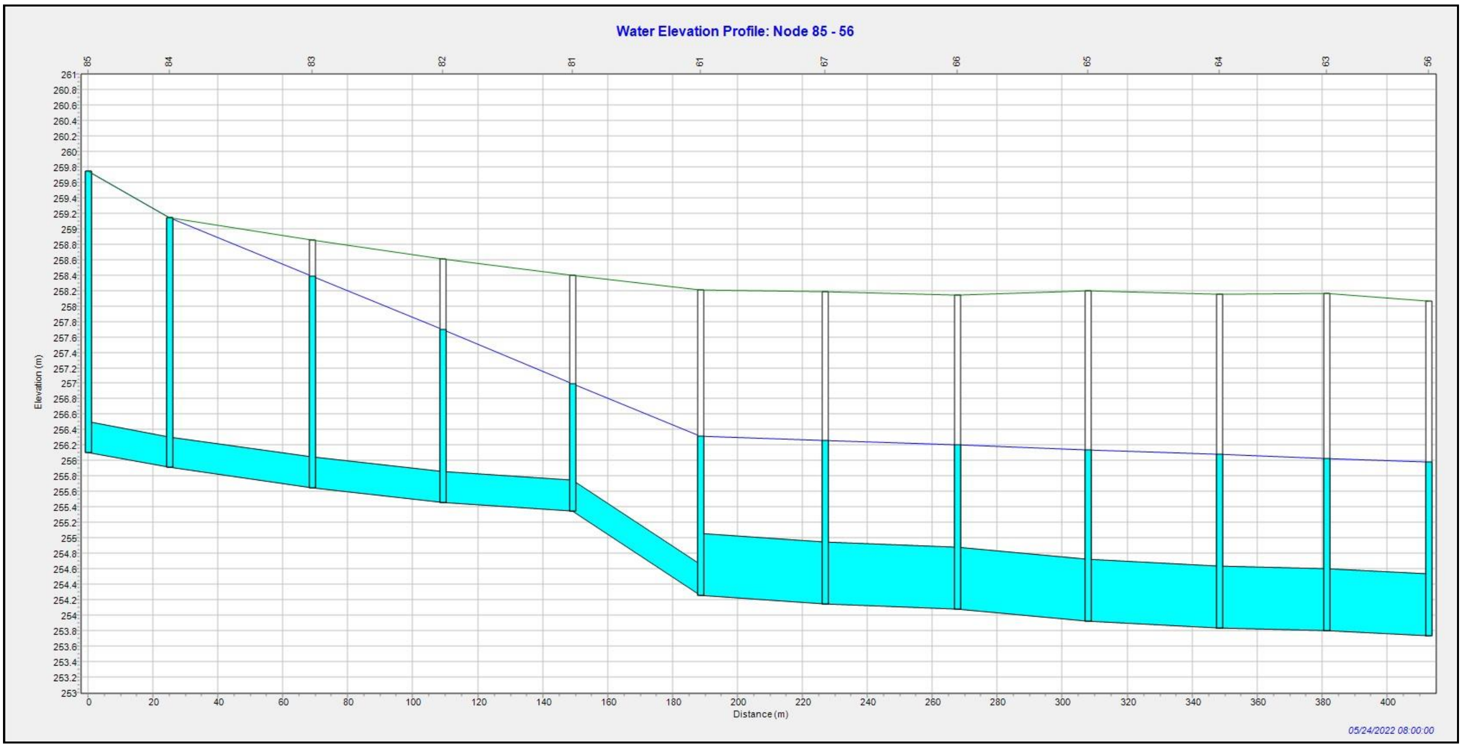
(A)


Water Elevation Profile: Node 33 - 17
Elevation (m)
Distance (m)
05/24/2022 08:00:00

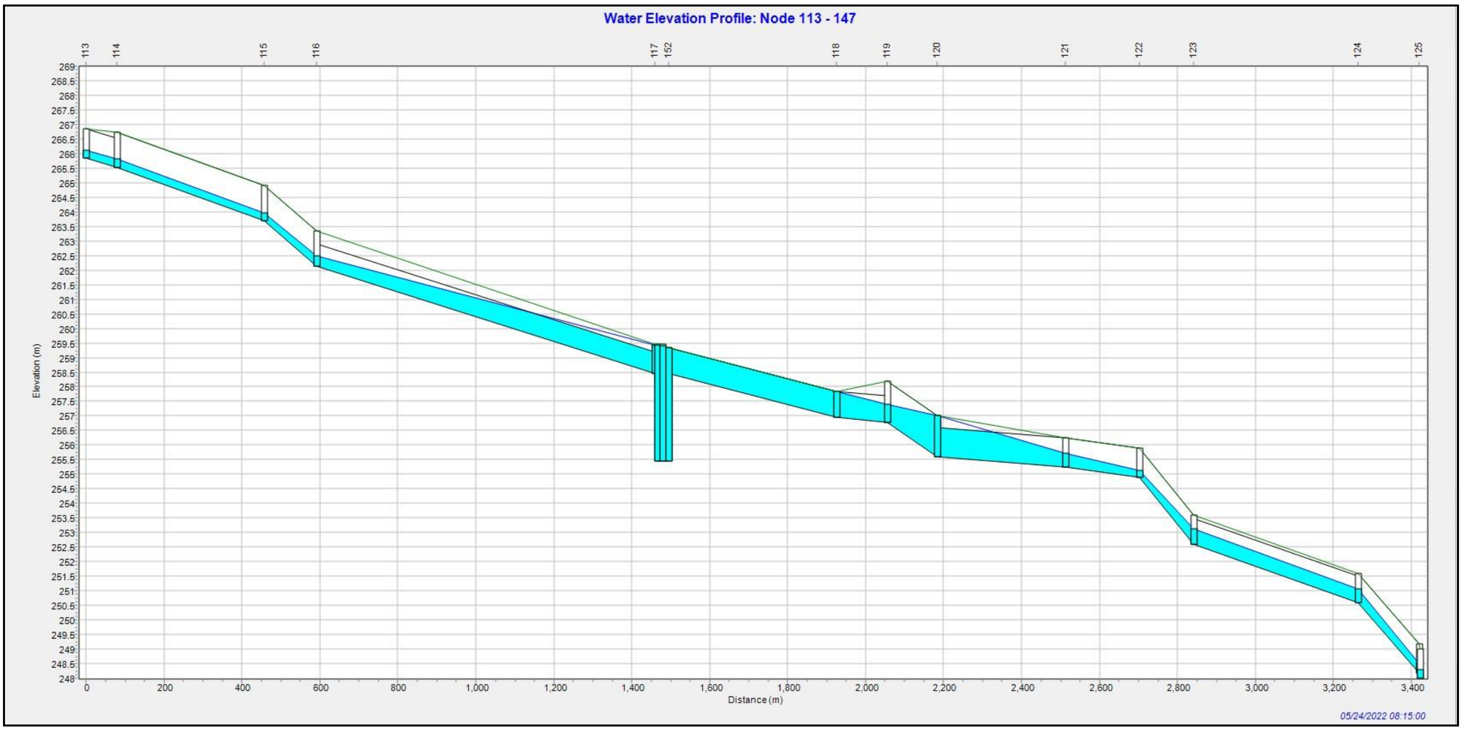
(B)


Water Elevation Profile: Node 127 - 56
Elevation (m)
Distance (m)
05/24/2022 08:00:00

(C)


Water Elevation Profile: Node 85 - 56
Elevation (m)
Distance (m)
05/24/2022 08:00:00

(D)



(E)

Figure (4-9). Water elevation profiles at 8.00 am A) WEP 37_34; B) WEP 85_56; C) WEP 127_56; D) WEP 33_17; E) WEP of Druento.

According to Figure (4-10), in the Druento channel rather than junction number 120, nodes 152, and 118 are in their maximum capacity range. It demonstrates conduit N.134 (the conduit between nodes 152 and 118) experienced heavy flooding.

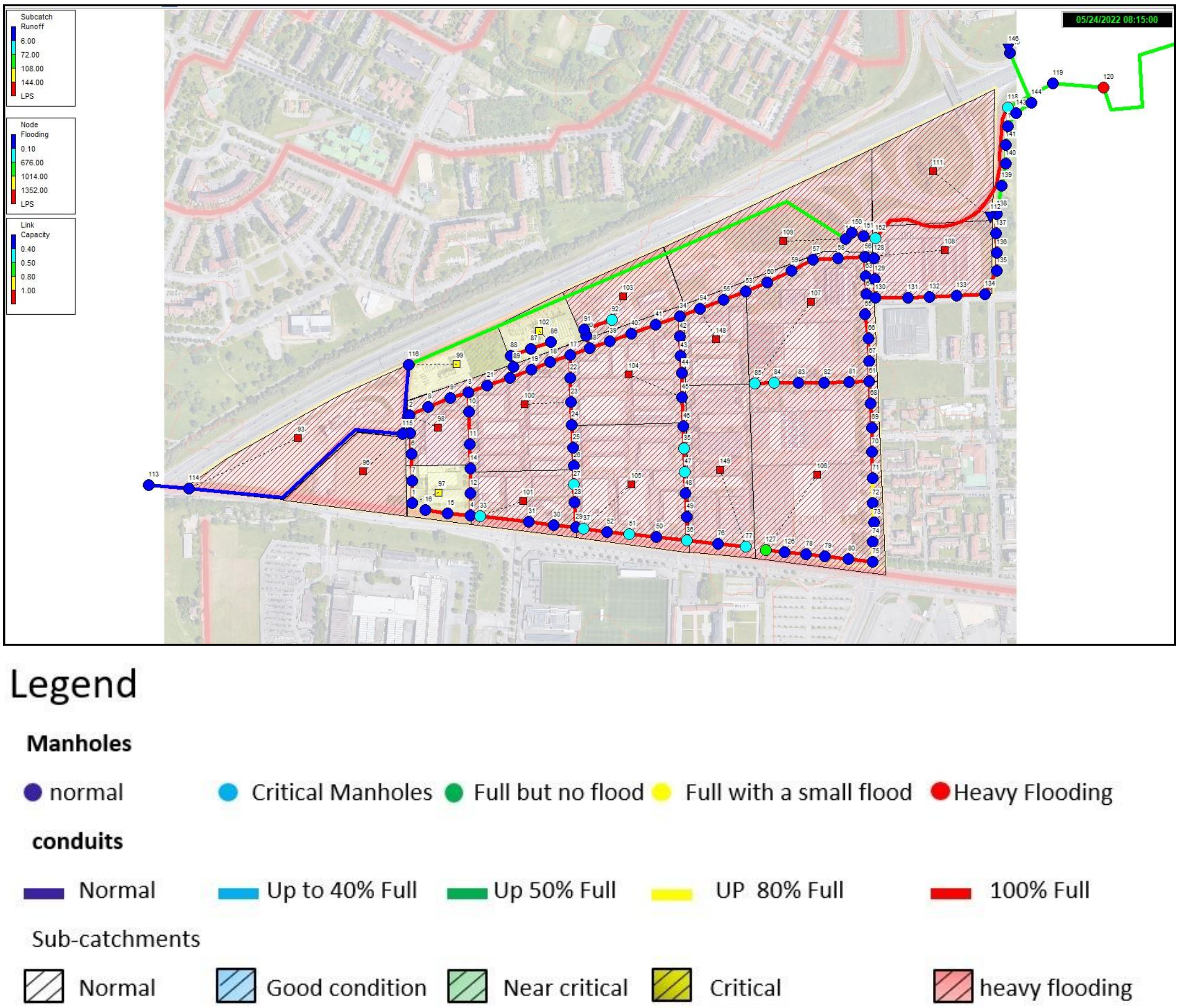


Figure (4-10). Druento runoff sub-catchment at 8:15 a.m.

It is noticeable that the predicted outcomes of the simulation such as flooded nodes and surface runoff, were accordingly confirmed by the observation of the Municipality of VR, thus showing the significant accuracy of the said simulation. Furthermore, the municipality of VR has observed flooding during rainfall and when farmers attempted to transport water to the other part of the city for irrigation purposes using the channel. Moreover, the observations indicated that certain sections of the Druento's channel can handle about 80% of its capacity (Figure 4-11). This may be attributed to the presence of seasonal accumulated tree leaves and branches that blocked the water passage lines.

Figure (4-11). Druento's WEP at 8:15 a.m.

4.3.1.2. Recorded Rainfall

The extracted information concerning precipitation, runoff, and flooding of VR based on RR data is shown in Figure (4-12). This image illustrates the volume of the entire system's precipitation, runoff, and flooding approximately during 24 hours of rainfall. Understandably, there are several critical hours of flooding in the system, but the most significant moment in the analysis occurs at 21:00. This particular time not only represents the maximum volume of the precipitation but also marks the peak runoff and flooding of the system happened. It should be mentioned from a considerable point of view, that the system flooding after 20 hours of rainfall stops, it is still steady, and it does not absorb or conduct water to another place.

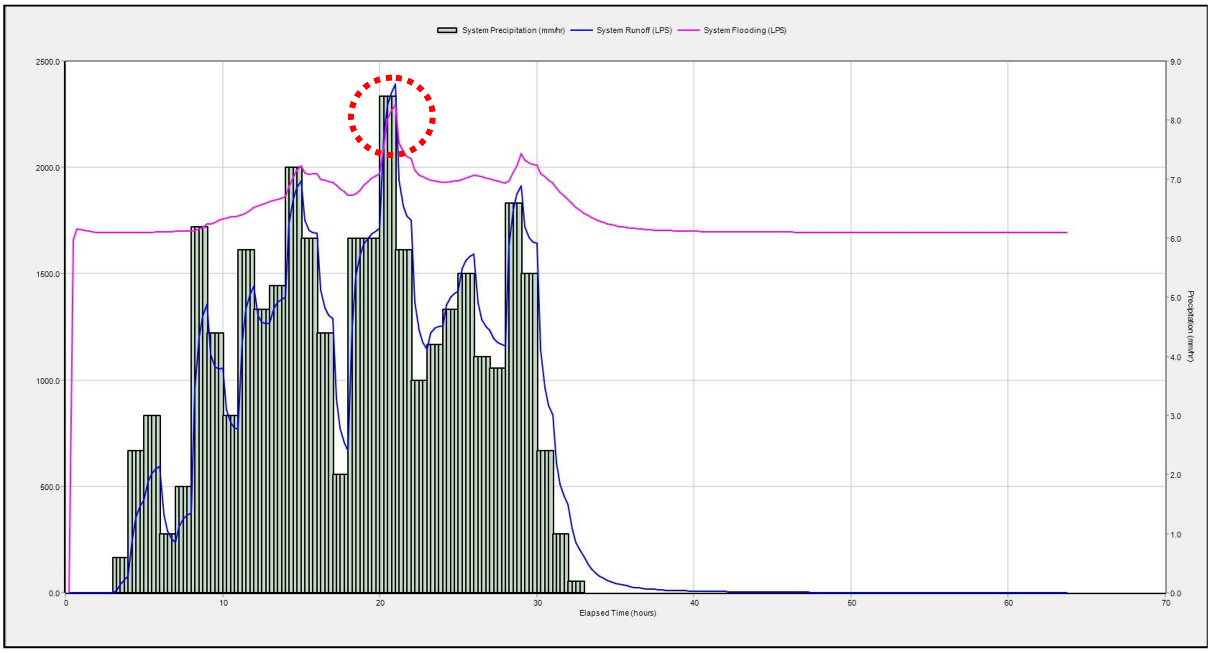


Figure (4-12). System precipitation, runoff, and flooding based on RR data.

Table (4-3) provides information on the maximum load of the available outfalls in the industrial area of VR. This information makes it understandable how much the load of the water discharge (LPS) is.

Table (4-3). Outfall loading extracted based on RR data.

Outfall Node	Flow Freq. Pcnt.	Avg. Flow LPS	Max. Flow LPS	Total Volume 10^6 ltr
112	88.24	54.52	134.12	6.906
146	99.92	1483.78	2452.46	213.028
147	99.82	1084.55	1088.79	155.405

Table 4 indicates information on the peak runoff and discharge of each sub-catchment separately due to the total precipitation of 125.40 mm. Understandably, sub-catchment number 106 exhibits the highest peak runoff at 354.39 LPS.

Table (4-4). Node details were extracted based on RR data.

Node	Hours Flooded	Maximum Rate LPS	Day of Maximum Flooding	Hour of Maximum Flooding	Total Flood Volume 10^6 ltr	Maximum Ponded Depth Meters
51	0.01	18.87	1	04:16	0.000	0.000
52	0.01	3.05	1	04:16	0.000	0.000
77	1.87	98.20	0	21:00	0.318	0.000
37	0.01	6.60	1	04:16	0.000	0.000
118	39.64	197.46	0	12:15	20.590	0.000
120	39.81	2050.16	0	00:25	293.635	0.000
127	7.72	125.22	0	21:00	1.088	0.000
150	0.01	2648.52	0	00:00	0.002	0.000
152	19.74	242.74	0	21:03	7.755	0.000

The analysis illustrates that one of the critical moments after the precipitation is going to start from 21:00 most of the sub-catchments are experiencing a surface flood except for those that are highlighted in yellow and green (Figure 4-13). The nodes showing the manholes illustrated that they may experience their maximum capacity (light blue), particularly, in node 120 flooding may start from the first hour of the rainfall. The current conduits and channel are still in good condition and no signs of flooding were observed. It should be noted that in both sections (section 1 and section 2) the initial manholes are connected to the sub-catchments. In fact, they cannot be considered reliable flooding indicators since they are the influent points where the sub-catchments are connected to the sewer system.

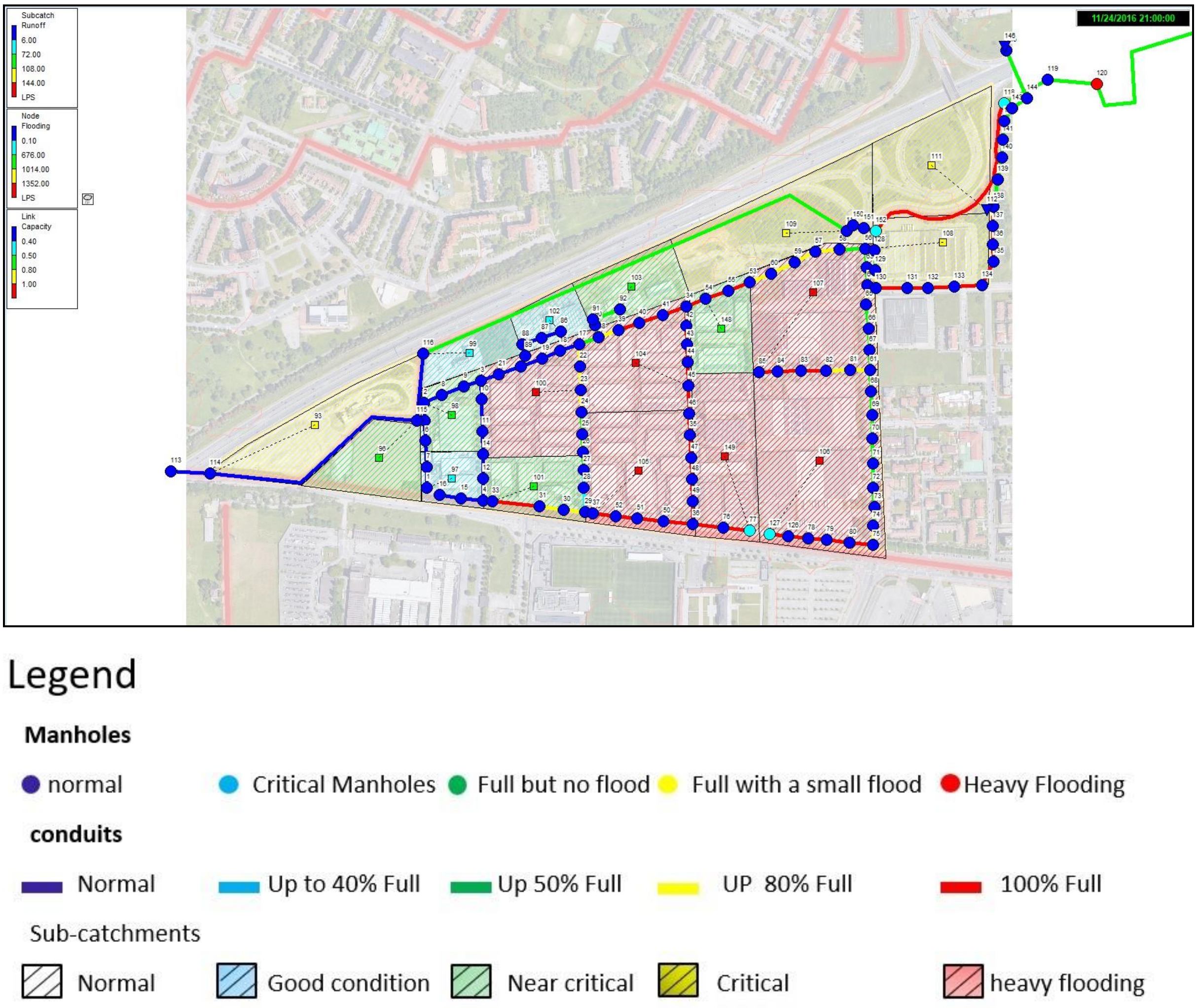
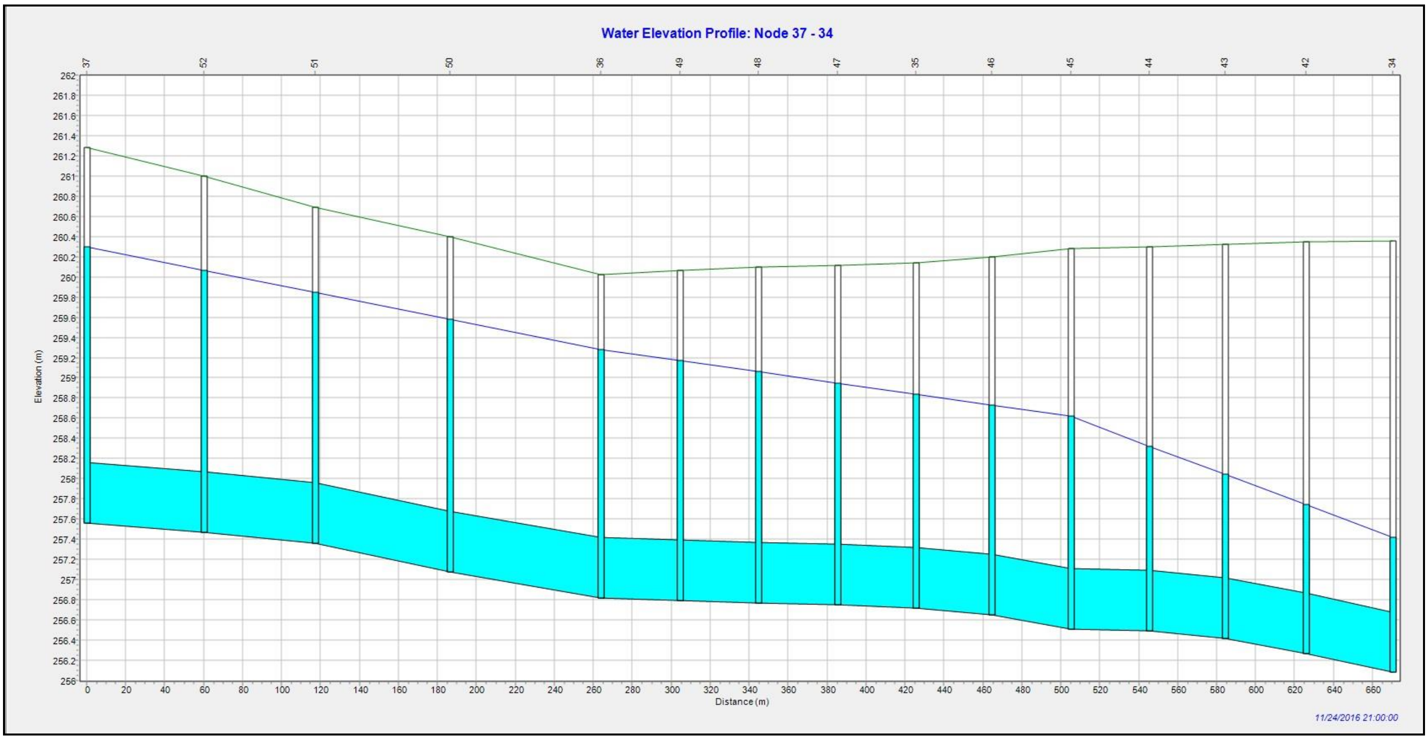
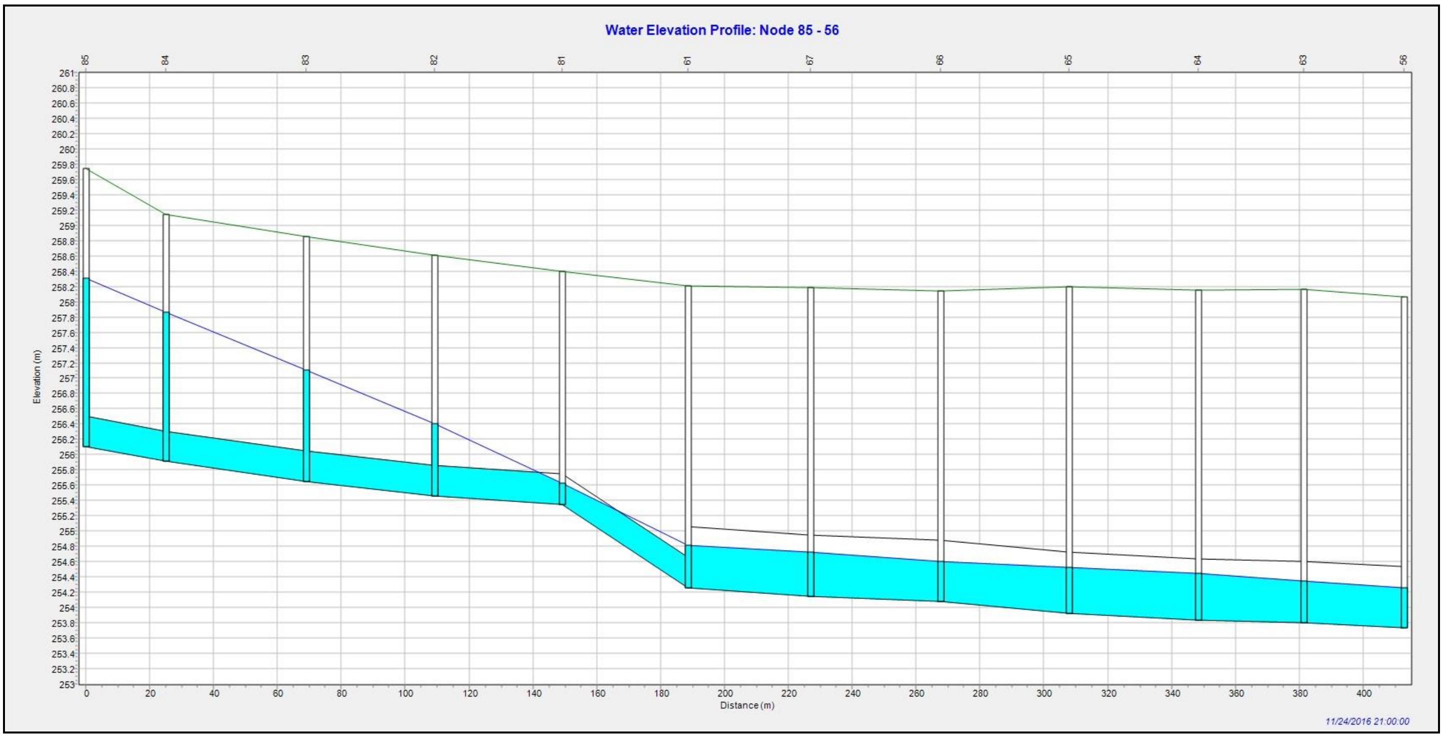


Figure (4-13). Sub-catchments at 21:00 after precipitation.

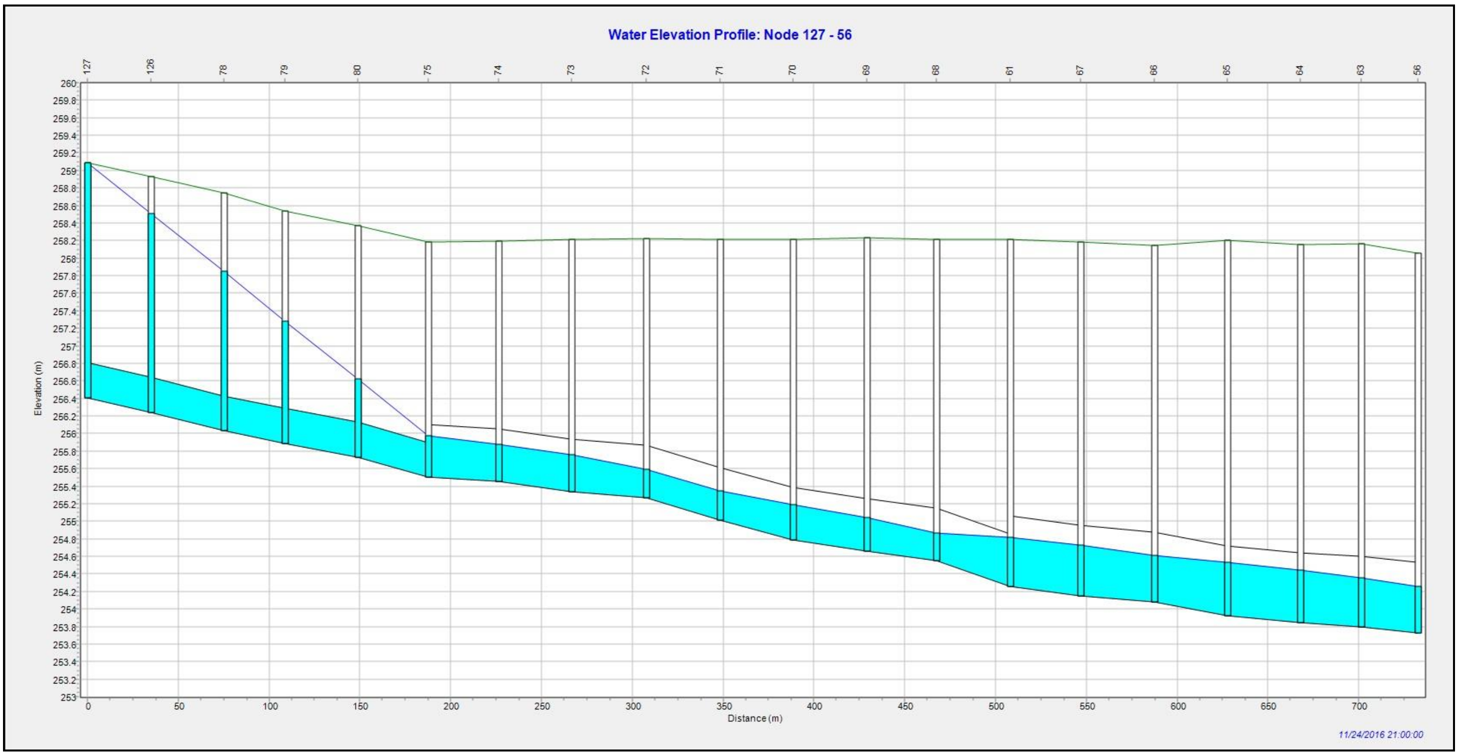
Figure (4-14) shows the critical WEP of VR at 21.00 which suggests the water flow/flooding in the region.


Water Elevation Profile: Node 37 - 34
Elevation (m)
Distance (m)
11/24/2016 21:00:00

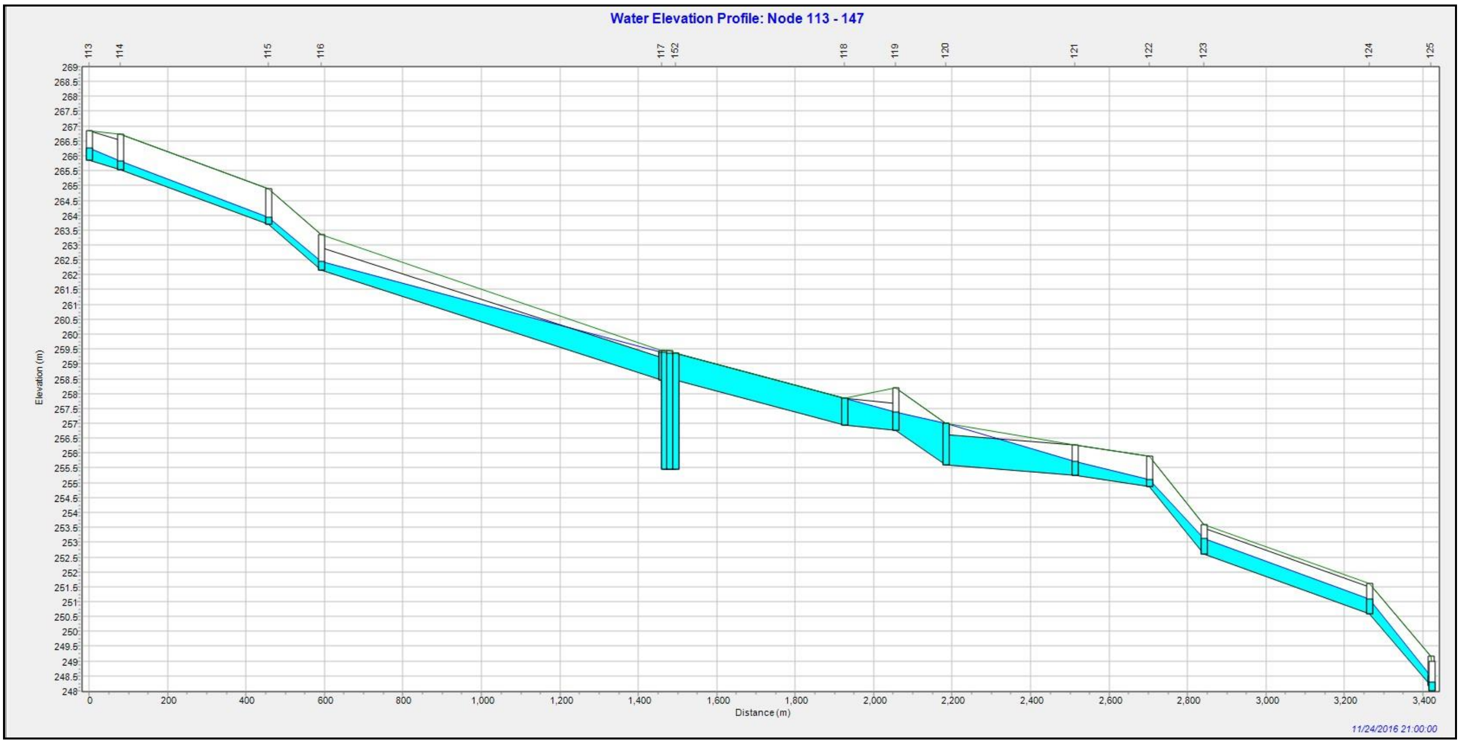
(A)


Water Elevation Profile: Node 85 - 56
Elevation (m)
Distance (m)
11/24/2016 21:00:00

(B)



(C)



(D)

Figure (4-14). Water elevation profiles at 21.00; A) WEP 37_34; B) WEP 85_56; C) WEP 127_56; D) WEP of Druento.

4.3.2. Scenario_01

In this scenario, the prime challenge was to modify and resize Druento's channel and find the optimized pathways connecting the sewer network to the channel. They were performed to hopefully address two key issues associated with water flow in the region: a) flooding in the Druento's channel; and b) peak runoff of the sewage system and bypassing the problematic portion of the water to the Druento's channel. Additionally, two different schemas were also involved in the analyses, which were modifying the channel with and without water pathways.

4.3.2.1. Design rainfall.

A) Modified channel without water-pathway

In the first phase of this modification, it was tried to identify the efficiency of resized Druento's channel. Figure (4-16) illustrates that duplicating the channel's size and replacing its material from concrete with a sustainable yet environmentally-friendly (Figure 4-15) material such as bio-swale is efficient in controlling flooding in the channel.

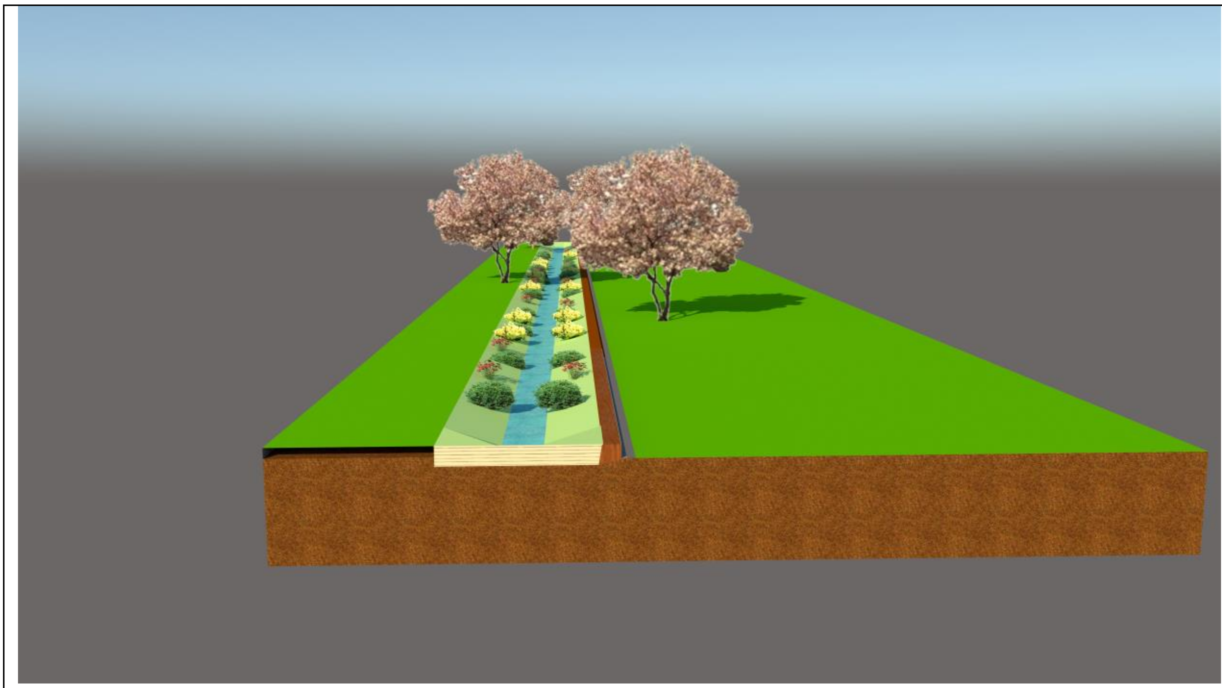


Figure (4-15). 3D model of an environmental-friendly channel (Bioswale).

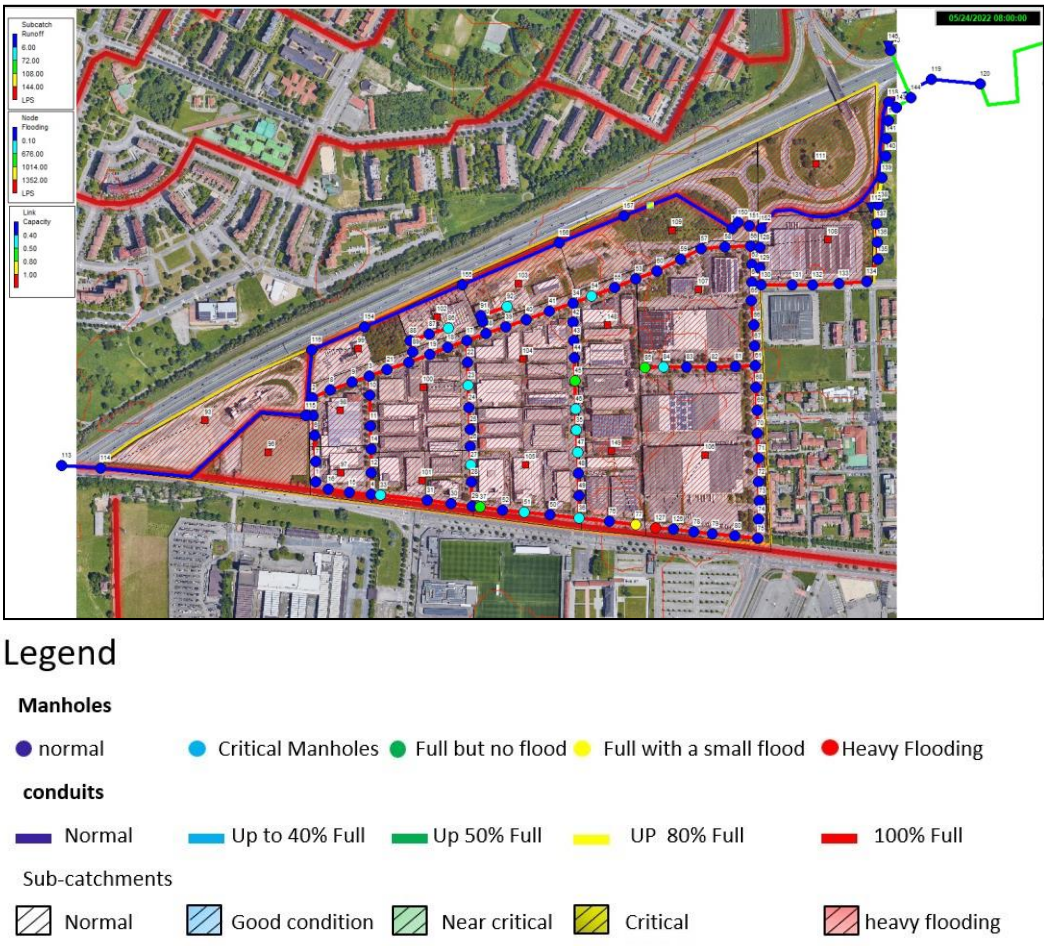
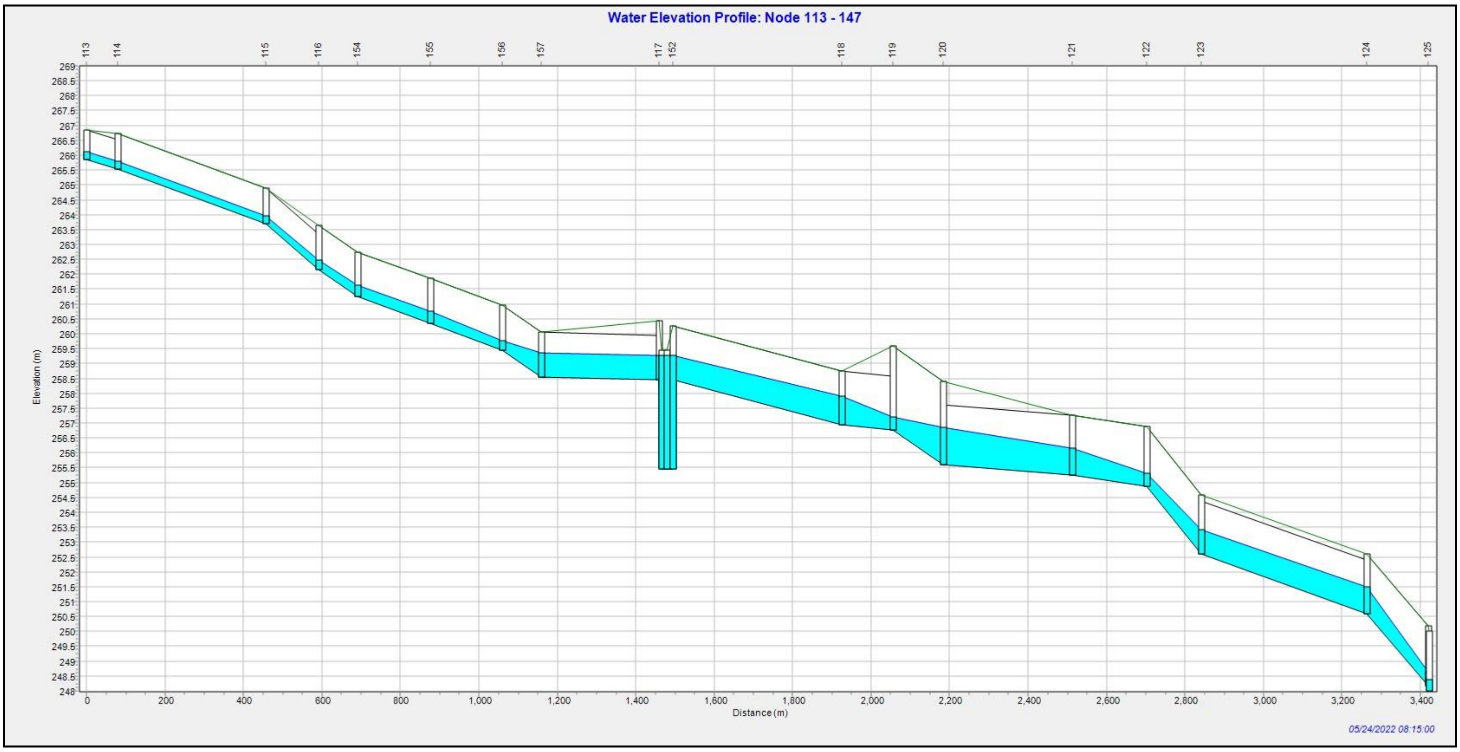
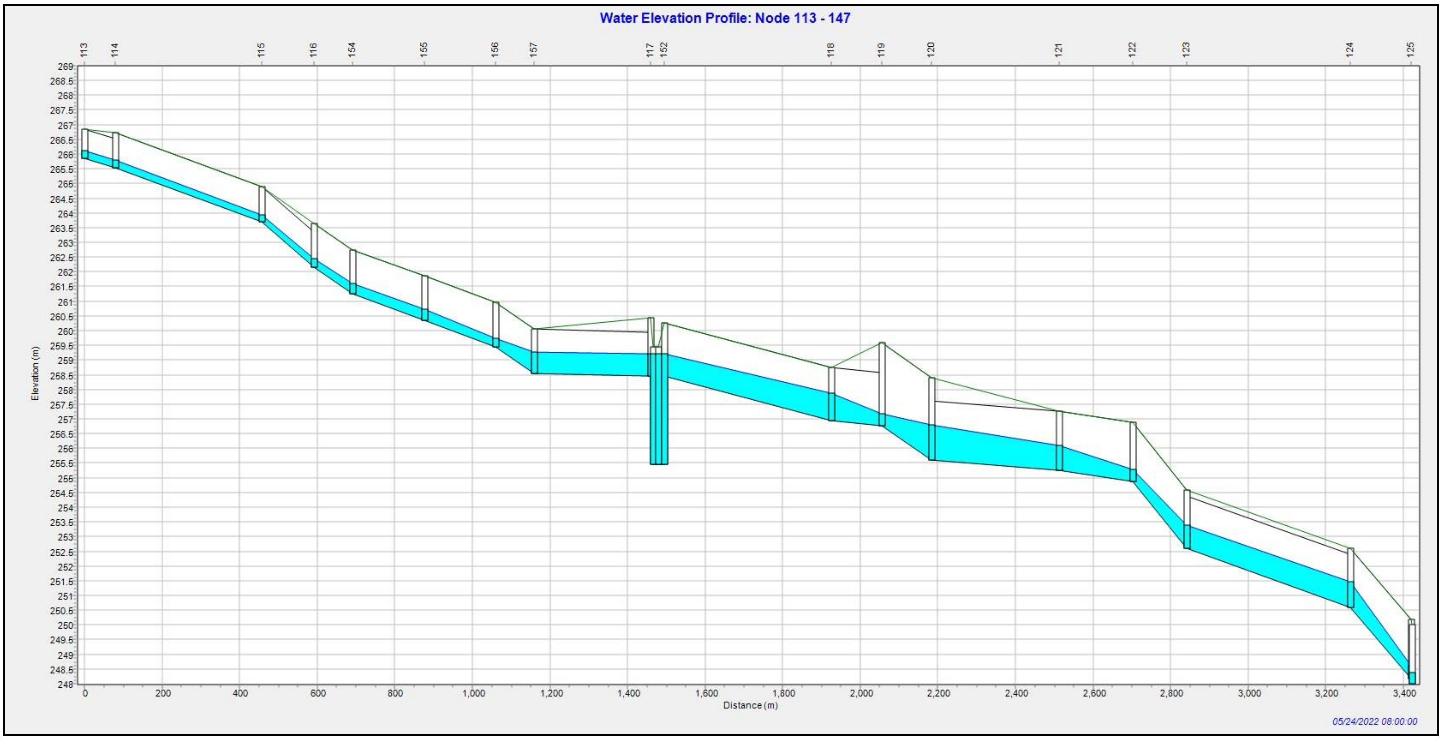


Figure (4-16). Sub-catchments at 8:00 a.m. without water-paths.

A straightforward comparison of water elevations in Druento’s channel during flooding moment highlights the effectiveness of this transition and it will be more understandable as shown in Figure (4-17). Furthermore, outfall loading, sub-catchment details, and node flooding information of VR are summarised in Tables (4-5) to (4-7).



(A)



(B)

Figure (4-17). Water elevation profiles of Druento at A) 8.00 am; B) 8.15 am.

Table (4-5). Outfall loading data of VR without considering water-pathways

Outfall Node	Flow Freq. Pcnt.	Avg. Flow LPS	Max. Flow LPS	Total Volume 10^6 ltr
112	98.59	50.94	367.94	8.456
146	99.96	1394.49	3157.54	235.155
147	99.74	2531.96	3420.53	425.218

Table (4-6). Sub-catchment details of VR without considering water-pathways

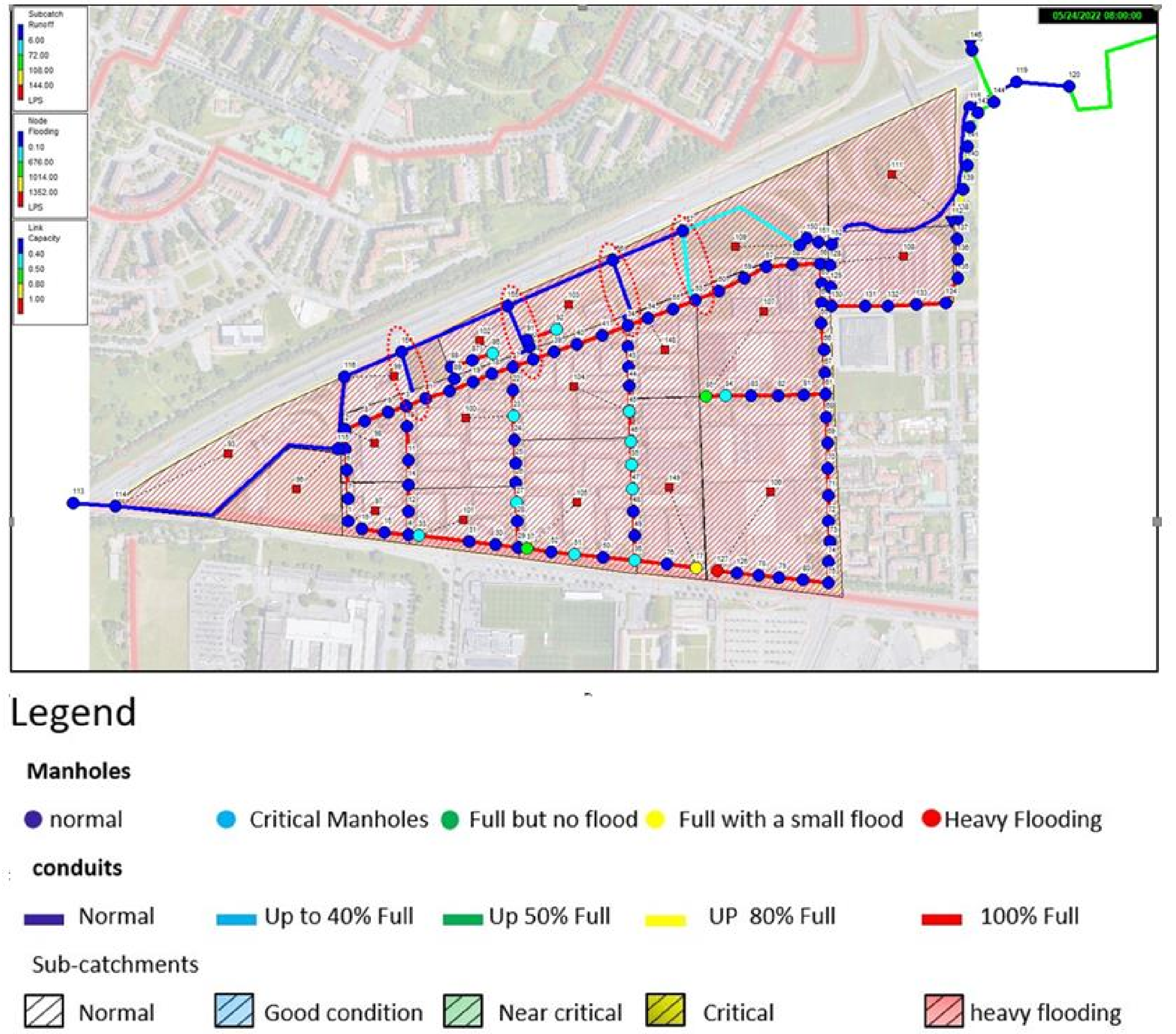
Subcatchment	Total Precip mm	Total Runon mm	Total Evap mm	Total Infil mm	Imperv Runoff mm	Perv Runoff mm	Total Runoff mm	Total Runoff 10^6 ltr	Peak Runoff LPS	Runoff Coeff
93	146.72	0.00	0.00	28.55	0.00	117.95	117.95	8.53	408.35	0.804
96	146.72	0.00	0.00	42.94	0.00	103.65	103.65	4.53	238.39	0.706
97	146.72	0.00	0.00	2.88	124.75	19.13	143.88	3.29	295.52	0.981
98	146.72	0.00	0.00	2.88	124.74	19.13	143.87	4.47	397.23	0.981
99	146.72	0.00	0.00	42.67	0.00	103.98	103.98	2.64	165.00	0.709
100	146.72	0.00	0.00	2.88	124.72	19.12	143.84	10.46	871.32	0.980
101	146.72	0.00	0.00	2.88	124.74	19.13	143.86	5.87	513.90	0.981
102	146.72	0.00	0.00	2.88	124.75	19.13	143.88	3.24	290.49	0.981
103	146.72	0.00	0.00	2.88	124.74	19.13	143.86	5.73	502.05	0.981
104	146.72	0.00	0.00	2.88	124.72	19.12	143.84	10.59	880.87	0.980
105	146.72	0.00	0.00	2.88	124.72	19.12	143.83	12.77	1038.36	0.980
106	146.72	0.00	0.00	2.89	124.70	19.11	143.81	22.22	1650.54	0.980
107	146.72	0.00	0.00	2.88	124.71	19.12	143.83	14.67	1169.63	0.980
108	146.72	0.00	0.00	7.87	105.66	33.20	138.86	7.75	649.37	0.946
109	146.72	0.00	0.00	66.33	0.00	80.11	80.11	7.99	282.81	0.546
111	146.72	0.00	0.00	43.48	0.00	102.99	102.99	8.46	367.94	0.702
148	146.72	0.00	0.00	2.88	124.74	19.13	143.86	5.44	478.23	0.981
149	146.72	0.00	0.00	2.88	124.72	19.12	143.84	10.36	863.87	0.980

Table (4-7). Node flooding without the path of VR without considering water-pathways

Node	Hours Flooded	Maximum Rate LPS	Day of Maximum Flooding	Hour of Maximum Flooding	Total Flood Volume 10^6 ltr	Maximum Ponded Depth Meters
12	0.01	11.37	0	07:38	0.000	0.000
15	0.01	4.74	0	07:38	0.000	0.000
23	0.48	605.19	0	08:00	0.467	0.000
24	0.01	0.32	0	07:38	0.000	0.000
27	0.78	285.00	0	07:52	0.627	0.000
31	0.01	0.15	0	07:34	0.000	0.000
43	0.01	0.27	0	07:52	0.000	0.000
44	0.01	0.29	0	07:52	0.000	0.000
45	0.48	701.82	0	08:00	0.531	0.000
46	0.51	26.84	0	07:50	0.047	0.000
47	0.60	0.57	0	07:52	0.001	0.000
49	0.01	0.11	0	07:38	0.000	0.000
51	1.11	10.49	0	07:42	0.040	0.000
54	0.02	7.57	0	08:00	0.000	0.000
77	5.98	1020.99	0	08:00	4.408	0.000
84	0.56	39.26	0	08:00	0.035	0.000
4	0.01	21.42	0	07:38	0.000	0.000
34	0.01	2.45	0	07:52	0.000	0.000
35	0.60	62.45	0	08:00	0.122	0.000
36	1.01	208.30	0	07:47	0.575	0.000
14	0.01	4.32	0	07:38	0.000	0.000
86	0.48	233.25	0	08:00	0.175	0.000
92	0.81	533.60	0	08:00	0.634	0.000
85	1.93	896.19	0	08:00	1.603	0.000
37	1.78	804.19	0	08:00	1.421	0.000
33	0.85	353.19	0	08:00	0.403	0.000
16	0.01	42.21	0	07:38	0.000	0.000
127	9.21	1452.95	0	08:00	5.712	0.000

B) Modified channel with water pathways

The second analysis was performed considering 4 pathways connecting the sewer system to Druento's channel. The outcomes from these pathways (Table 4-8 to 10) illustrated that they are entirely ineffective due to the creation of a backflow inside the channels which can disturb the function of the sewage network. It means that while these pathways that were supposed to transport the overloaded water to the Druento's channel to reduce the load of the sewer system at the peak runoffs, push the overloaded volume of the Druento's channel into the sewer system instead. This affects the entire drainage system adversely and makes the situation even worse because they only transfer the irrigation water into the sewer system (Figure 4-18 & 19).



Note: Red circles indicate the created conduits

Figure (4-18). Sub-catchments at 8:00 a.m. with water-paths.

Table (4-8). Sub-catchment details considering water pathways.

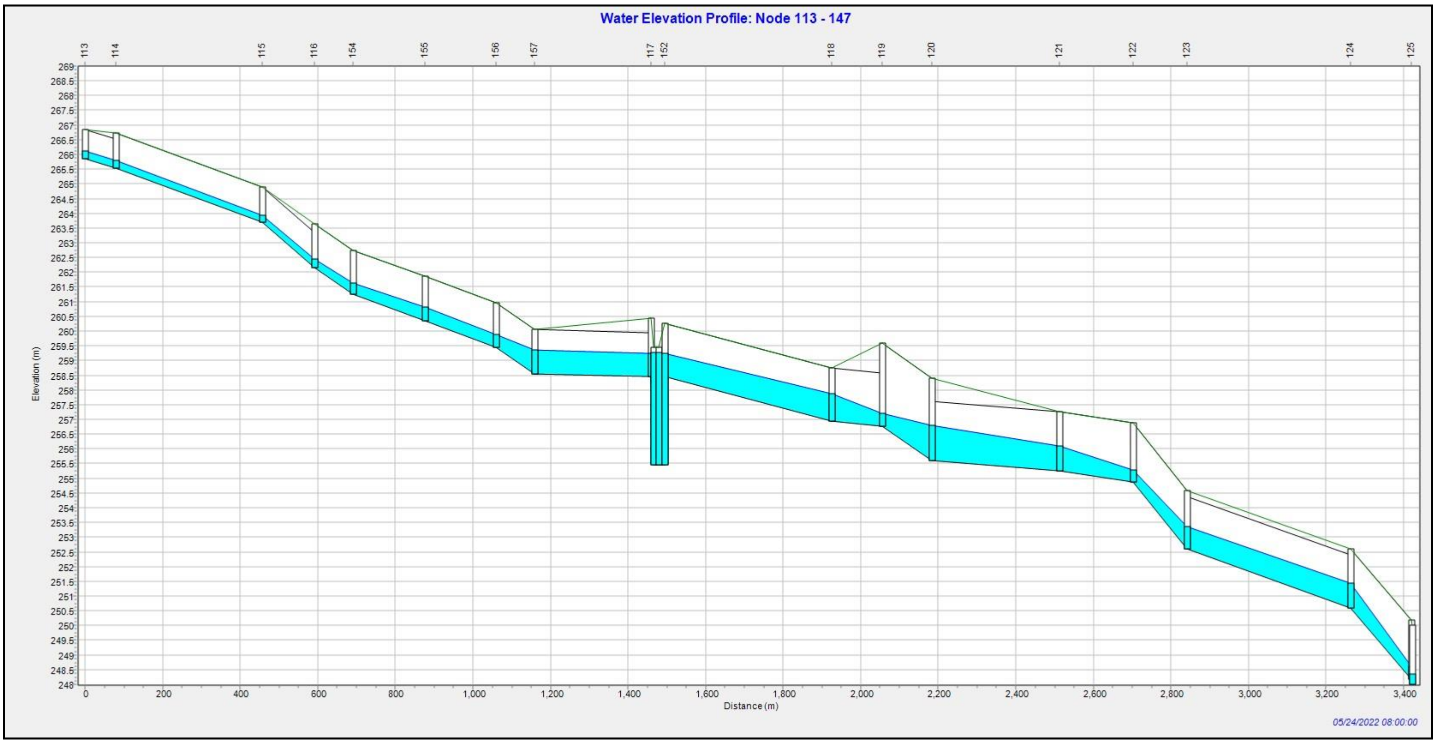
Subcatchment	Total Precip mm	Total Runon mm	Total Evap mm	Total Infil mm	Imperv Runoff mm	Perv Runoff mm	Total Runoff mm	Total Runoff 10^6 ltr	Peak Runoff LPS	Runoff Coeff
93	146.72	0.00	0.00	28.55	0.00	117.95	117.95	8.53	408.35	0.804
96	146.72	0.00	0.00	42.94	0.00	103.65	103.65	4.53	238.39	0.706
97	146.72	0.00	0.00	2.88	124.75	19.13	143.88	3.29	295.52	0.981
98	146.72	0.00	0.00	2.88	124.74	19.13	143.87	4.47	397.23	0.981
99	146.72	0.00	0.00	42.67	0.00	103.98	103.98	2.64	165.00	0.709
100	146.72	0.00	0.00	2.88	124.72	19.12	143.84	10.46	871.32	0.980
101	146.72	0.00	0.00	2.88	124.74	19.13	143.86	5.87	513.90	0.981
102	146.72	0.00	0.00	2.88	124.75	19.13	143.88	3.24	290.49	0.981
103	146.72	0.00	0.00	2.88	124.74	19.13	143.86	5.73	502.05	0.981
104	146.72	0.00	0.00	2.88	124.72	19.12	143.84	10.59	880.87	0.980
105	146.72	0.00	0.00	2.88	124.72	19.12	143.83	12.77	1038.36	0.980
106	146.72	0.00	0.00	2.89	124.70	19.11	143.81	22.22	1650.54	0.980
107	146.72	0.00	0.00	2.88	124.71	19.12	143.83	14.67	1169.63	0.980
108	146.72	0.00	0.00	7.87	105.66	33.20	138.86	7.75	649.37	0.946
109	146.72	0.00	0.00	66.33	0.00	80.11	80.11	7.99	282.81	0.546
111	146.72	0.00	0.00	43.48	0.00	102.99	102.99	8.46	367.94	0.702
148	146.72	0.00	0.00	2.88	124.74	19.13	143.86	5.44	478.23	0.981
149	146.72	0.00	0.00	2.88	124.72	19.12	143.84	10.36	863.87	0.980

Table (4-9). Sub-catchment details without considering water pathways.

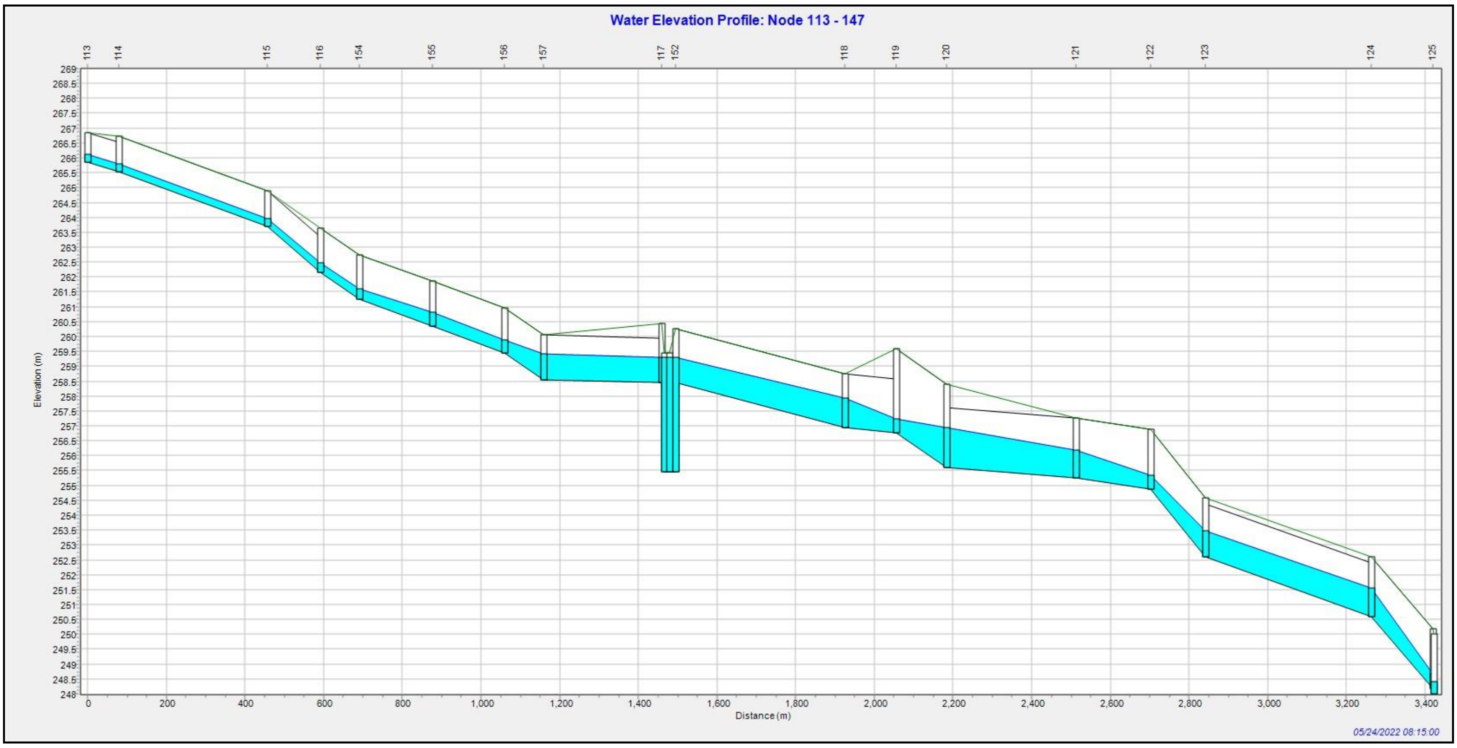
Outfall Node	Flow Freq. Pcnt.	Avg. Flow LPS	Max. Flow LPS	Total Volume 10^6 ltr
112	98.59	50.94	367.94	8.456
146	99.96	1657.29	3185.98	279.397
147	99.74	2261.73	3686.36	379.837

Table (4-10). Node flooding without considering water pathways.

Node	Hours Flooded	Maximum Rate LPS	Day of Maximum Flooding	Hour of Maximum Flooding	Total Flood Volume 10^6 ltr	Maximum Ponded Depth Meters
12	0.01	10.76	0	07:30	0.000	0.000
15	0.01	7.03	0	07:30	0.000	0.000
23	0.27	279.73	0	08:00	0.137	0.000
27	0.91	284.98	0	08:05	0.519	0.000
31	0.01	0.02	0	07:33	0.000	0.000
45	0.51	476.77	0	08:00	0.391	0.000
46	0.57	26.84	0	07:52	0.052	0.000
47	0.72	0.46	0	08:00	0.001	0.000
49	0.01	0.02	0	08:06	0.000	0.000
51	1.69	10.49	0	07:25	0.062	0.000
77	7.95	1020.93	0	08:00	5.871	0.000
84	1.38	45.05	0	08:00	0.074	0.000
4	0.01	17.08	0	07:30	0.000	0.000
35	0.72	62.45	0	07:49	0.144	0.000
36	1.64	208.24	0	08:02	0.980	0.000
14	0.01	6.58	0	07:30	0.000	0.000
86	0.39	146.96	0	08:00	0.095	0.000
92	0.99	378.99	0	08:00	0.471	0.000
85	1.96	896.12	0	08:00	1.639	0.000
37	1.96	804.12	0	08:00	1.464	0.000
33	0.93	353.15	0	08:00	0.407	0.000
16	0.01	46.43	0	07:30	0.000	0.000
127	9.21	1457.81	0	08:00	5.740	0.000

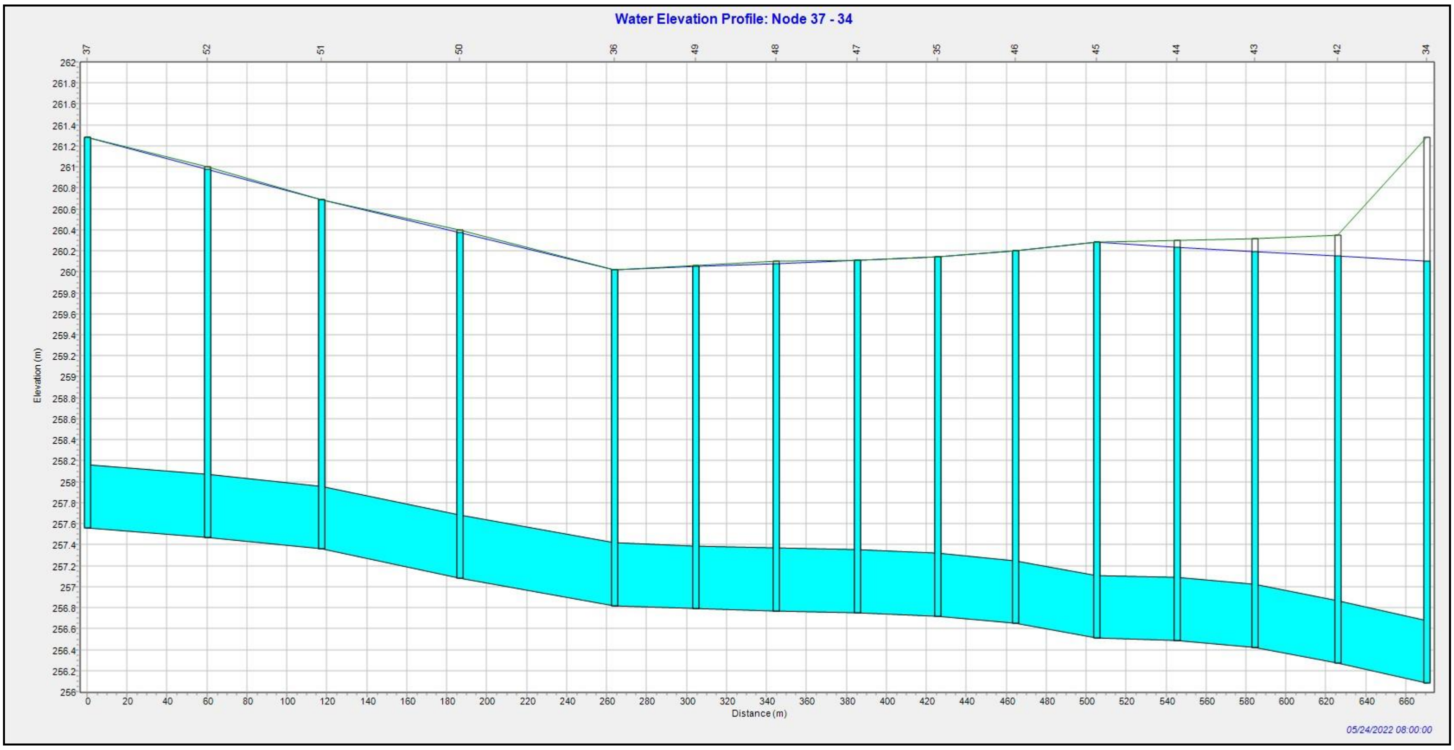


(A)



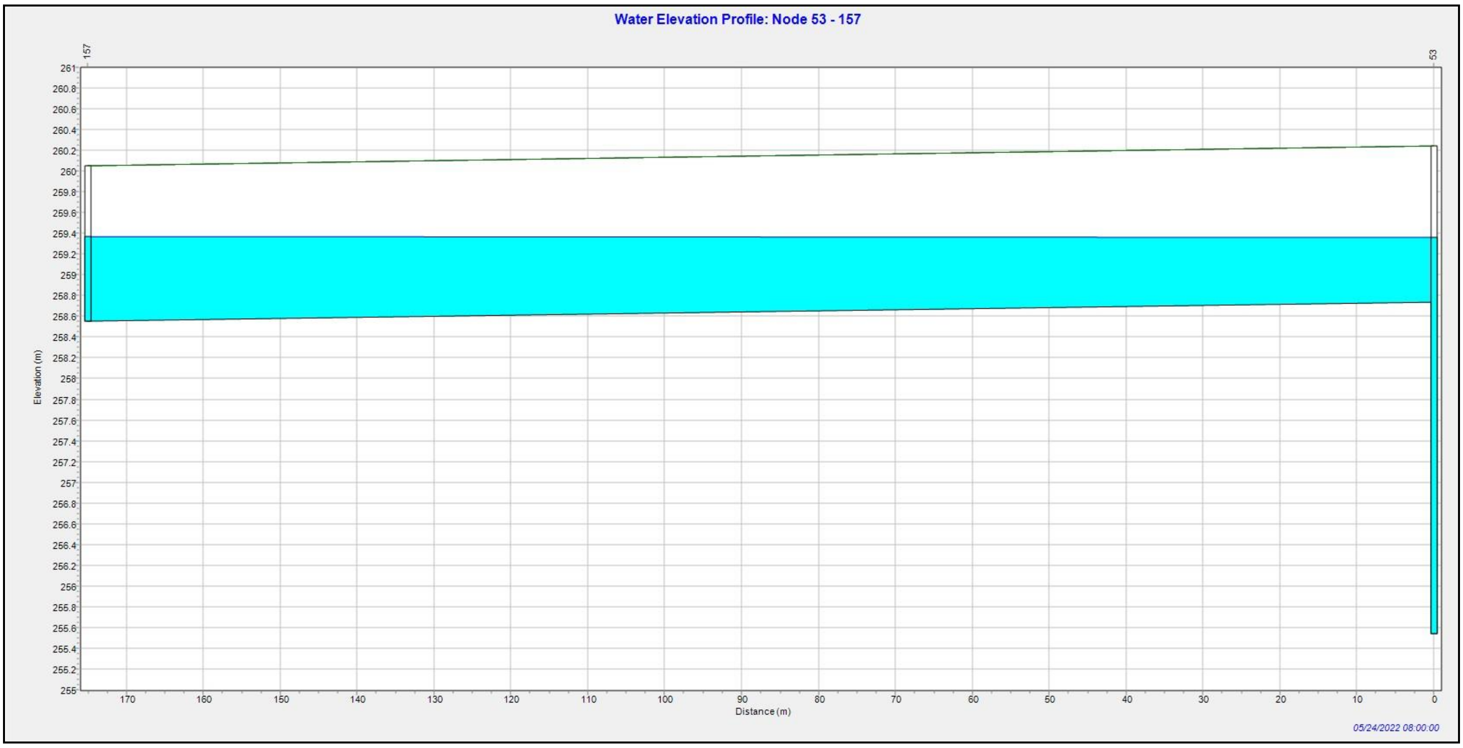
Water Elevation Profile: Node 113 - 147
Elevation (m)
Distance (m)
05/24/2022 08:15:00

(B)



Water Elevation Profile: Node 37 - 34
Elevation (m)
Distance (m)
05/24/2022 08:00:00

(C)



(D)

Figure (4-19). Water elevation profiles of Druneto at; A) 8.00 am B) 8.15 am C) WEP of node 34-37 at 8:00 am; D) WEP of the new path 53-157 at 8:00 am.

4.3.2.2. Recorded Rainfall

A) Modified channel without water pathways

In the next phase of this investigation, the efficiency of the Druento channel was evaluated after replacing the concrete with environmentally friendly natural bio-swale as the channel base material. The modification of the Druento channel exhibited a higher bio-swale-based channel compared to the old concrete one. Similar to the previous steps, the most important factor in this replacement, is the modification of the roughness according to **ASCE (1982).** Overall, the results of this scenario showed a slight variation compared to those of Scenario 01_A confirming the successful resolution of the overloading issue in the Druento channel and securing the prohibition of flooding. This is also supported by the sub-catchments and WEP information shown in Figures (4-20 & 21) as well as node flooding, Outfall loading, and Sub-catchment details provided in Tables (4- 11 to 13).

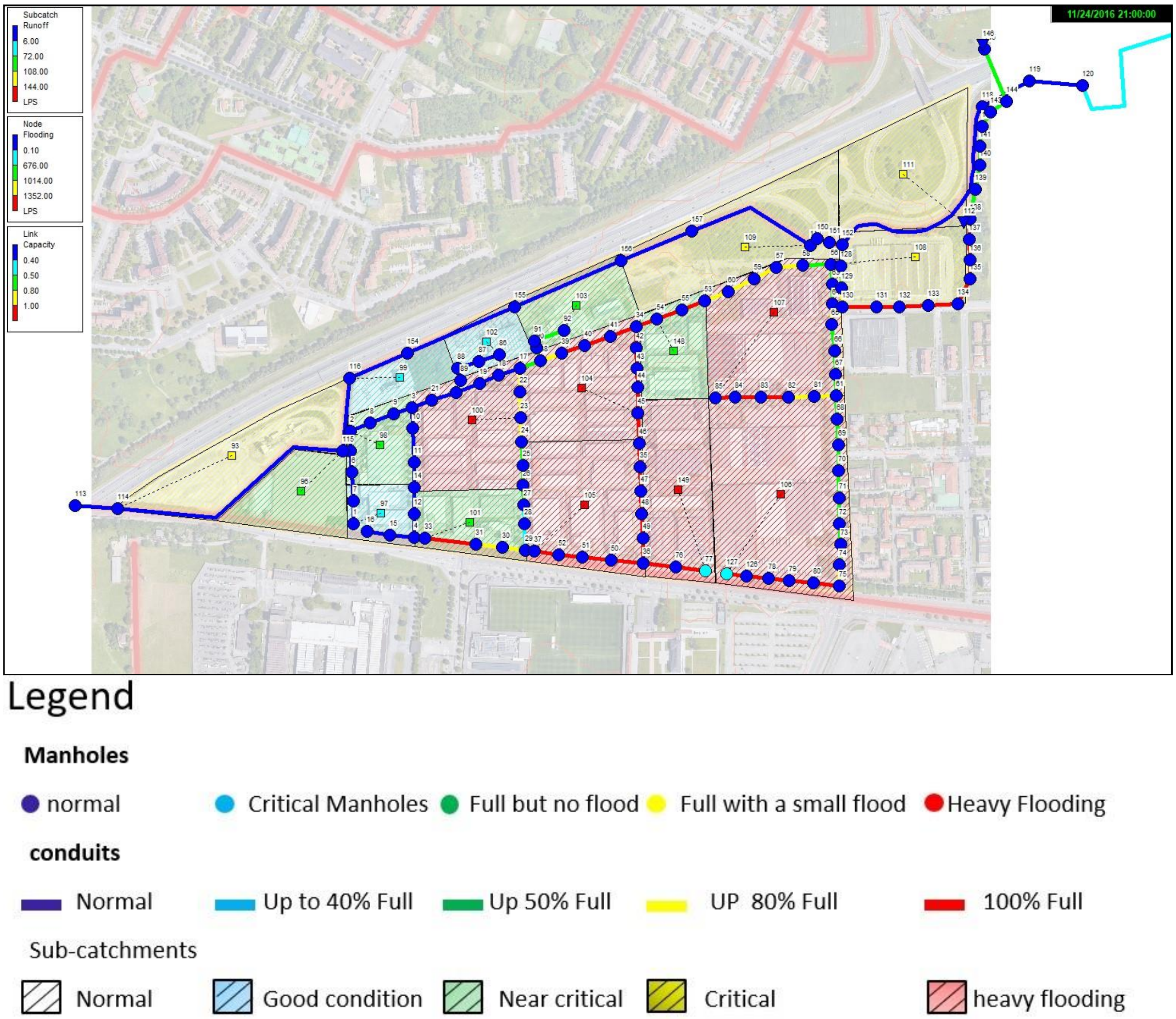


Figure (4-20). Sub-catchments at 21:00 without water pathways.

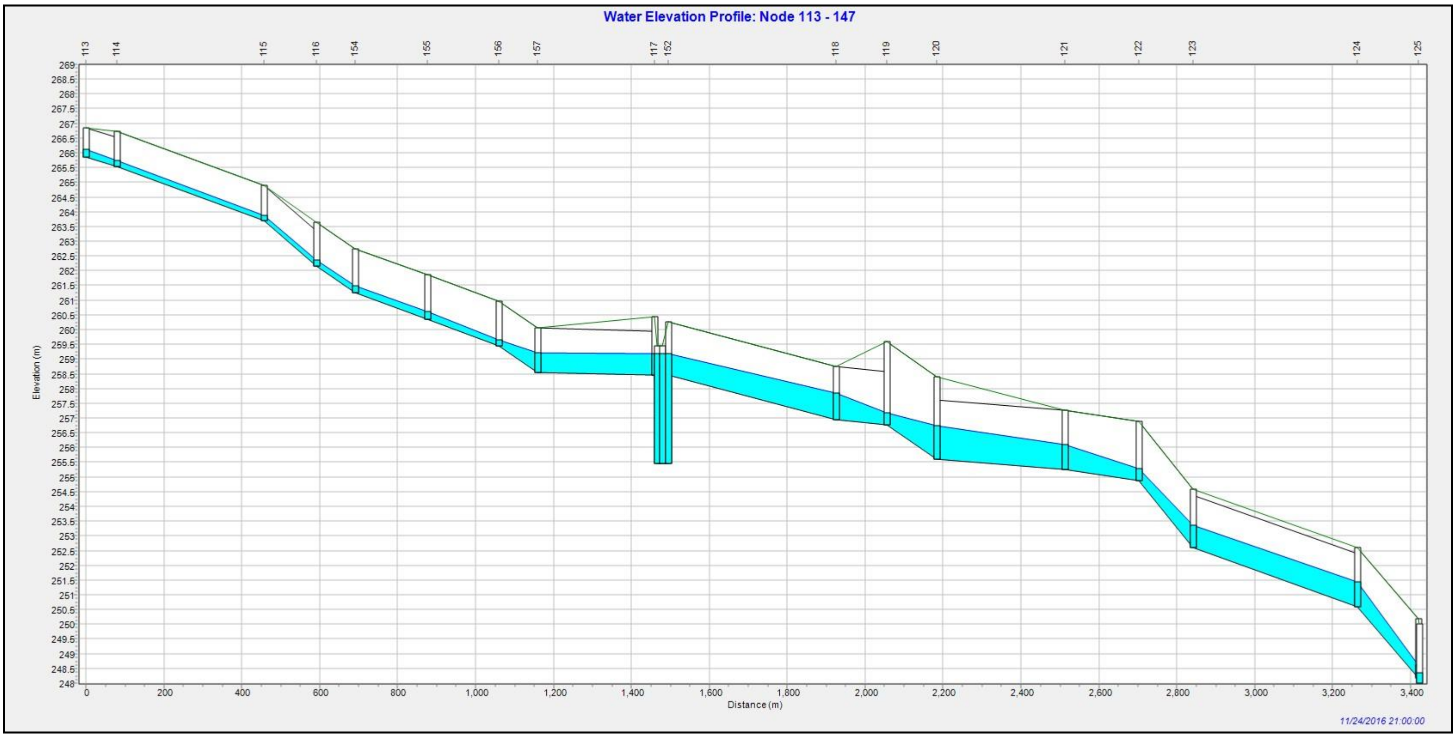


Figure (4-21). Water Elevation Profiles of Druneto in without water pathways at 21:00.

Table (4-11). Node flooding data without water pathways.

Node	Hours Flooded	Maximum Rate LPS	Day of Maximum Flooding	Hour of Maximum Flooding	Total Flood Volume 10^6 ltr	Maximum Ponded Depth Meters
51	0.01	19.06	1	04:16	0.000	0.000
52	0.01	2.94	1	04:16	0.000	0.000
77	1.87	98.20	0	21:00	0.318	0.000
37	0.01	6.59	1	04:16	0.000	0.000
127	7.72	125.22	0	21:00	1.088	0.000

Table (4-12). Node flooding data without water pathways.

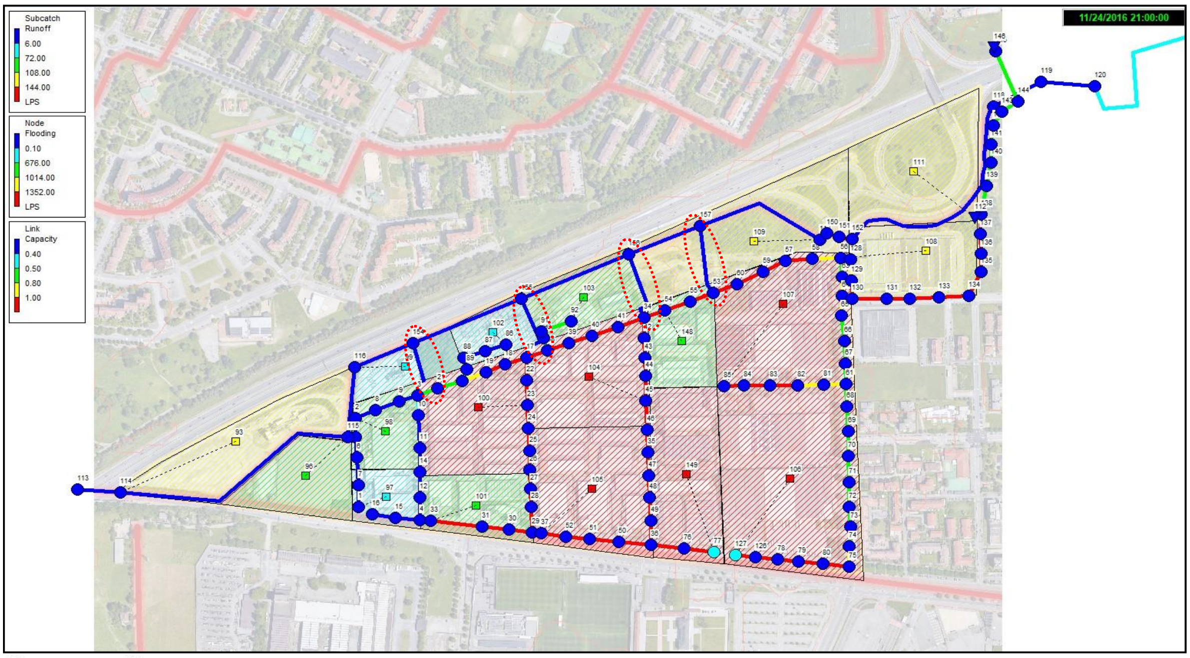
Outfall Node	Flow Freq. Pcnt.	Avg. Flow LPS	Max. Flow LPS	Total Volume 10^6 ltr
112	88.47	54.52	134.12	6.906
146	99.95	1485.43	2452.42	213.027
147	99.69	2524.68	2771.10	360.372

Table (4-13). Sub-catchment details without water pathways.

Subcatchment	Total Precip mm	Total Runon mm	Total Evap mm	Total Infil mm	Imperv Runoff mm	Perv Runoff mm	Total Runoff mm	Total Runoff 10^6 ltr	Peak Runoff LPS	Runoff Coeff
93	125.40	0.00	0.00	27.17	0.00	97.52	97.52	7.05	136.14	0.778
96	125.40	0.00	0.00	40.41	0.00	84.60	84.60	3.70	76.31	0.675
97	125.40	0.00	0.00	2.82	106.58	15.99	122.57	2.81	53.04	0.977
98	125.40	0.00	0.00	2.82	106.57	15.99	122.56	3.81	72.02	0.977
99	125.40	0.00	0.00	40.39	0.00	84.80	84.80	2.15	46.09	0.676
100	125.40	0.00	0.00	2.82	106.55	15.98	122.53	8.91	168.12	0.977
101	125.40	0.00	0.00	2.82	106.57	15.98	122.55	5.00	94.47	0.977
102	125.40	0.00	0.00	2.82	106.58	15.99	122.57	2.76	52.11	0.977
103	125.40	0.00	0.00	2.82	106.57	15.98	122.55	4.88	92.16	0.977
104	125.40	0.00	0.00	2.82	106.55	15.98	122.53	9.02	170.19	0.977
105	125.40	0.00	0.00	2.82	106.54	15.98	122.52	10.88	205.12	0.977
106	125.40	0.00	0.00	2.82	106.51	15.96	122.47	18.92	354.39	0.977
107	125.40	0.00	0.00	2.82	106.54	15.97	122.51	12.50	235.34	0.977
108	125.40	0.00	0.00	7.60	90.27	27.48	117.74	6.57	126.20	0.939
109	125.40	0.00	0.00	59.96	0.00	64.49	64.49	6.43	121.36	0.514
111	125.40	0.00	0.00	40.47	0.00	84.12	84.12	6.91	134.12	0.671
148	125.40	0.00	0.00	2.82	106.57	15.98	122.55	4.63	87.53	0.977
149	125.40	0.00	0.00	2.82	106.55	15.98	122.53	8.82	166.51	0.977

B) Modified channel with water-path

Similar to the outcomes of scenario 01_B of the Design Rainfall, the same outcomes were derived. This analysis confirmed that the new water pathways are entirely ineffective as well. Also, similar to the previous step (scenario 01_2_A) the peak hour of the runoff is 21:00. Tables (4-14 to 16) and Figures (4-22 &23) confirm these results vividly.



Legend

Manholes

normal | Critical Manholes | Full but no flood | Full with a small flood | Heavy Flooding

conduits

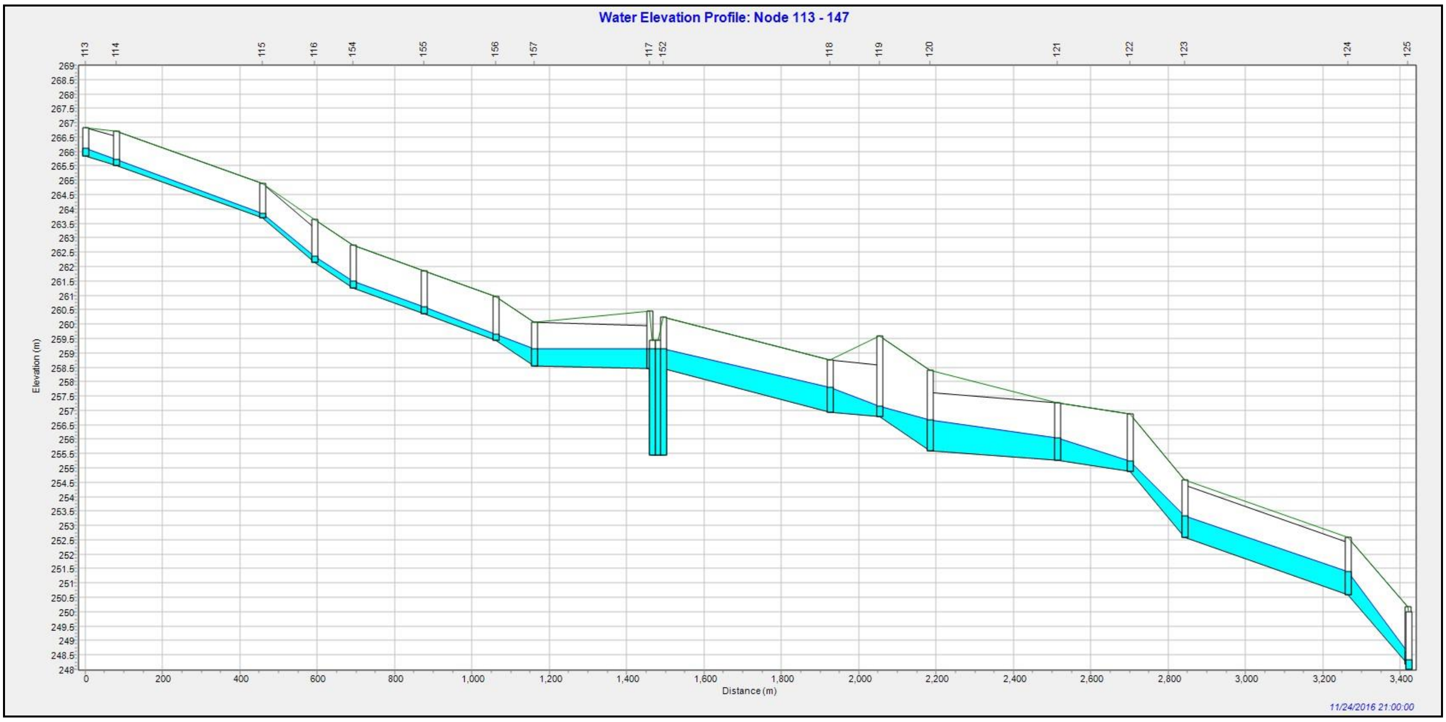
Normal | Up to 40% Full | Up 50% Full | UP 80% Full | 100% Full

Sub-catchments

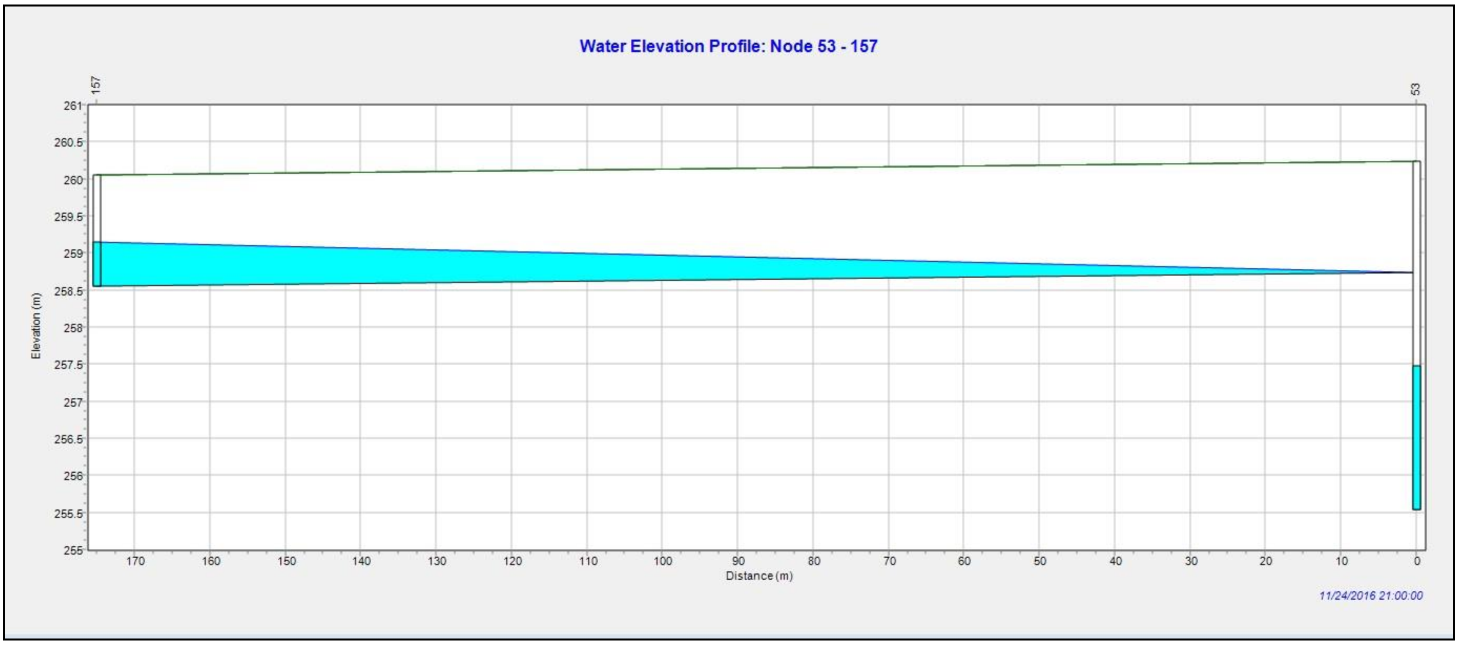
Normal | Good condition | Near critical | Critical | heavy flooding

The conduits inside represent the new water pathways

Figure (4-22). Sub-catchments at 21:00 without water-paths



(A)



(B)

Figure (4-23). Water elevation profiles of A) Druento channel at 21:00; B) 53-157 at 21:00.

Table (4-14). Node flooding data with water pathways.

Node	Hours Flooded	Maximum Rate LPS	Day of Maximum Flooding	Hour of Maximum Flooding	Total Flood Volume 10^6 ltr	Maximum Ponded Depth Meters
51	0.01	4.06	1	04:16	0.000	0.000
52	0.01	18.36	1	04:16	0.000	0.000
77	3.64	187.90	0	21:00	0.824	0.000
37	0.01	6.96	1	04:16	0.000	0.000
127	7.72	125.22	0	21:00	1.088	0.000

Table (4-15). Outfall loading data with water pathways.

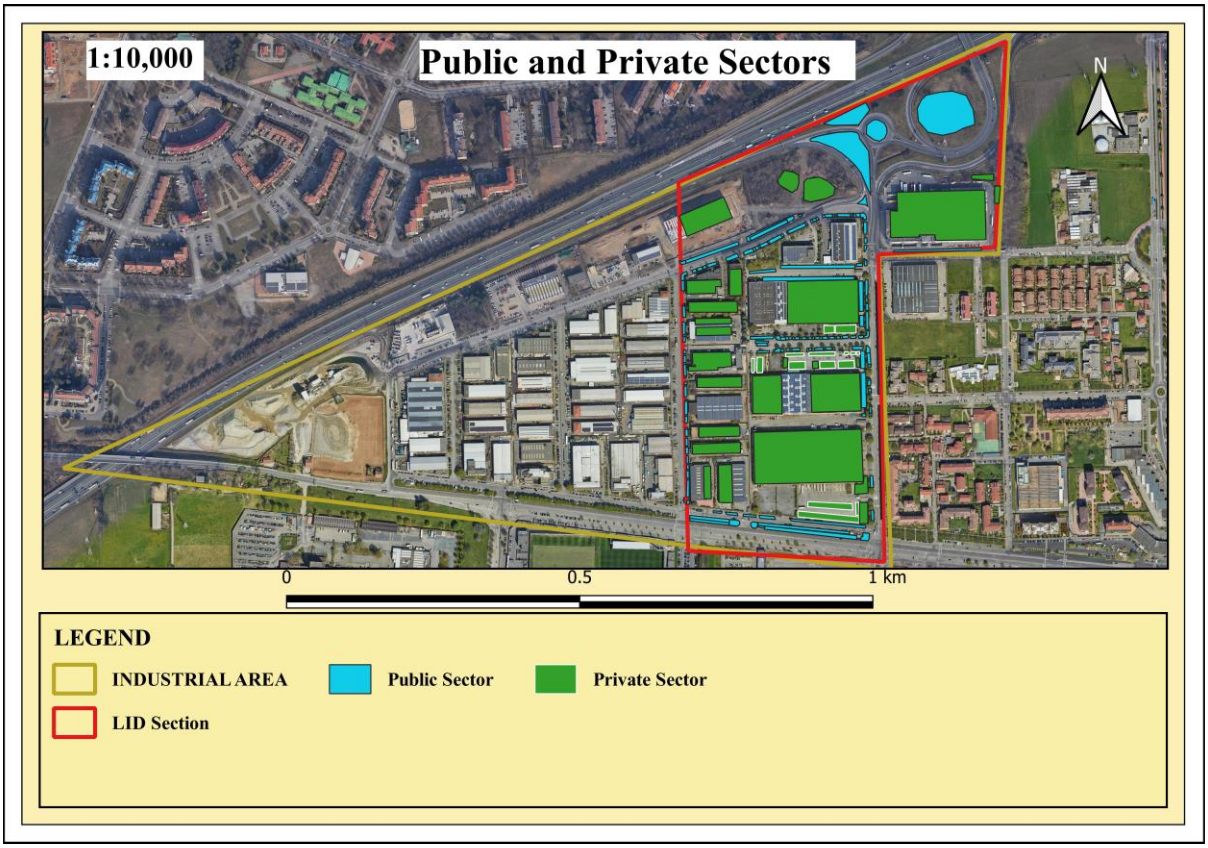
Outfall Node	Flow Freq. Pcnt.	Avg. Flow LPS	Max. Flow LPS	Total Volume 10^6 ltr
112	88.47	54.52	134.12	6.906
146	99.95	1760.49	2683.86	252.399
147	99.69	2246.00	2439.17	320.594

Table (4-16). Sub-catchment details with water pathways.

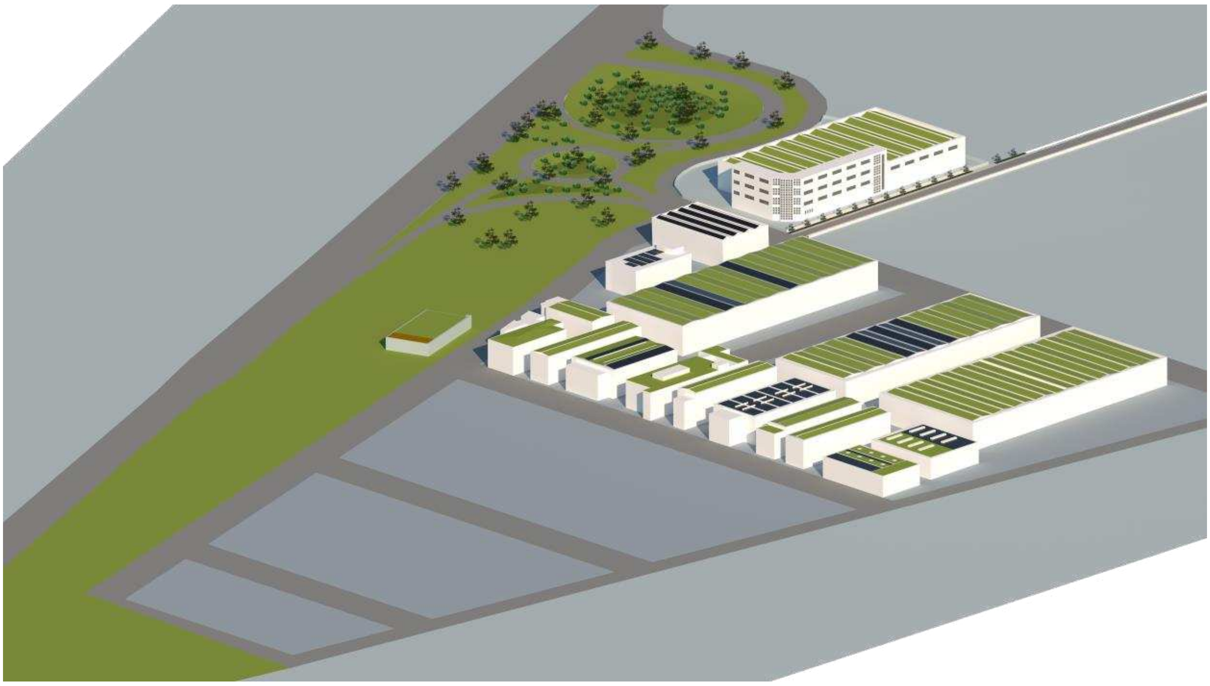
Subcatchment	Total Precip mm	Total Runon mm	Total Evap mm	Total Infil mm	Imperv Runoff mm	Perv Runoff mm	Total Runoff mm	Total Runoff 10^6 ltr	Peak Runoff LPS	Runoff Coeff
93	125.40	0.00	0.00	27.17	0.00	97.52	97.52	7.05	136.14	0.778
96	125.40	0.00	0.00	40.41	0.00	84.60	84.60	3.70	76.31	0.675
97	125.40	0.00	0.00	2.82	106.58	15.99	122.57	2.81	53.04	0.977
98	125.40	0.00	0.00	2.82	106.57	15.99	122.56	3.81	72.02	0.977
99	125.40	0.00	0.00	40.39	0.00	84.80	84.80	2.15	46.09	0.676
100	125.40	0.00	0.00	2.82	106.55	15.98	122.53	8.91	168.12	0.977
101	125.40	0.00	0.00	2.82	106.57	15.98	122.55	5.00	94.47	0.977
102	125.40	0.00	0.00	2.82	106.58	15.99	122.57	2.76	52.11	0.977
103	125.40	0.00	0.00	2.82	106.57	15.98	122.55	4.88	92.16	0.977
104	125.40	0.00	0.00	2.82	106.55	15.98	122.53	9.02	170.19	0.977
105	125.40	0.00	0.00	2.82	106.54	15.98	122.52	10.88	205.12	0.977
106	125.40	0.00	0.00	2.82	106.51	15.96	122.47	18.92	354.39	0.977
107	125.40	0.00	0.00	2.82	106.54	15.97	122.51	12.50	235.34	0.977
108	125.40	0.00	0.00	7.60	90.27	27.48	117.74	6.57	126.20	0.939
109	125.40	0.00	0.00	59.96	0.00	64.49	64.49	6.43	121.36	0.514
111	125.40	0.00	0.00	40.47	0.00	84.12	84.12	6.91	134.12	0.671
148	125.40	0.00	0.00	2.82	106.57	15.98	122.55	4.63	87.53	0.977
149	125.40	0.00	0.00	2.82	106.55	15.98	122.53	8.82	166.51	0.977

4.3.3. Scenario_02

In this section, the main focus of the investigation was on the application of LID controllers to realize their performances in managing and mitigating the effects of flooding and surface runoffs in VR. Similar to the previous scenarios, DR and RR were considered as two different batches of feed data. The intentional separation of the study into several subschemas ensured an in-depth analysis of the LID controllers' performance in a variety of environmental circumstances and it enhanced the study's depth and applicability. Figure (4-24), provides the applied LID practices by the stakeholder types (private and public sectors).



(A)



(B)

Figure (4-24). Focus section that; A) LID controllers divided into public and private sections, and B) the 3D model by application of the LID controllers.

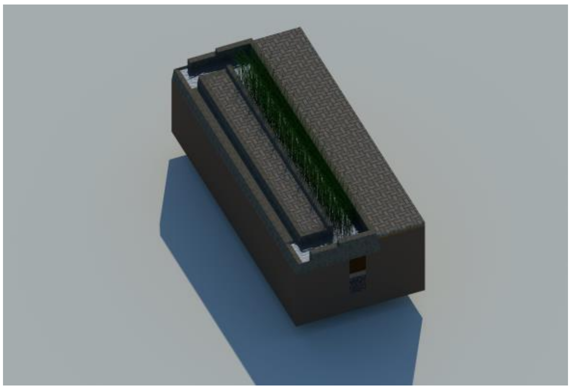
4.3.2.3. Design Rainfall

In this defined scenario, an investigation was performed to study the impacts of four types of LID controllers, namely, green roofs, permeable pavement, rain gardens, and bio-retention cells (Figure 4-25). The objective of this implementation was first, to comprehensively analyse each LID individually within the specified sub-catchments, and second, to assess their influences in terms of efficiency and runoff control. The analytical focus was on the DR to provide a targeted and detailed evaluation within this subset. A careful analysis was carried out using the DR data, while the quantitative features of this research were vividly observed (Table 4-17). The table summarises the spatial coverage of each type of LID controller that provides information on their individual and cross-effects in the VR. This analysis aims to clarify the subtle relationships and contributions of the several LID controllers to reduce surface runoffs in the studied area.

A

B

C



D

Figure (4-25). Green Infrastructure samples; A) green roof; B) rain garden; C) permeable pavement; D) bio-retention Cell.

Table (4-17). Sub-catchments and details of the LID practices.

Block	**Total Area (ha)**	**Impervious Area (ha)**	**Pervious Area (ha)**	**Green Roof Area (ha)**	**Permeable Pavement (ha)**	**Rain Garden Area (ha)**	**Bio-Retention cell Area (ha)**	**Impervious (%)**	**[1]ImATrGr (%)**	**[2]PerATRa (%)**	**[3]PerATPePa %**	**ImATrBiRc (%)**
106	7.58	7.28	0.3	2.15	0.63	0.13	0.30	96.0	29.6	43.3	8.7	4.1
107	4.54	4.38	0.16	0.77	0.5	NA	0.20	96.5	17.5	NA	11.4	4.6
108	2.66	2.33	0.33	1.08	0.06	0.06	NA	87.6	46.4	18.8	2.5	NA
109	5.15	1.07	4.08	0.26	NA	0.98	NA	20.8	24.7	24.0	NA	NA
111	4.06	1.09	2.97	[5]NA	NA	0.4	NA	26.8	NA	13.5	NA	NA
148	1.51	1.51	NA	0.41	0.14	NA	0.03	100.0	27.0	NA	9.2	1.9
149	3.43	3.38	0.067	0.69	0.20	0.02	0.05	98.5	20.4	25.4	5.9	1.5

1. Percentage of impervious area treated for green roofs.
2. Percentage of the pervious area treated for the rain garden.
3. Percentage of pervious area treated for permeable pavement.
4. Percentage of impervious area treated for bio-retention cells.
5. Not applicable.

In this section, seven sub-catchments were analysed, taking into account the use of LID controllers (Figure 4-26). As a result, it is possible to directly compare the peak runoff in these sub-catchments to those seen in the previous scenarios (Tables 4-18 to 20). The results clearly show a significant decrease in peak runoff. For example, sub-catchment number 11, indicated a high runoff of 367.94 L/s in scenarios_00 and scenarios_01. Unexpectedly this peak runoff decreased dramatically in the current scenario, falling to a modest 94.84 L/s. This significant decrease is evidence proving the implemented LID controllers' ability to effectively mitigate peak runoff that represents a significant improvement compared to the previous situations.

(A)

(B)

Figure (4-26). Sub-catchment details at A) 8.00 am B) 7:45 am.

Table (4-18). Sub-catchment details at 8.00 am.

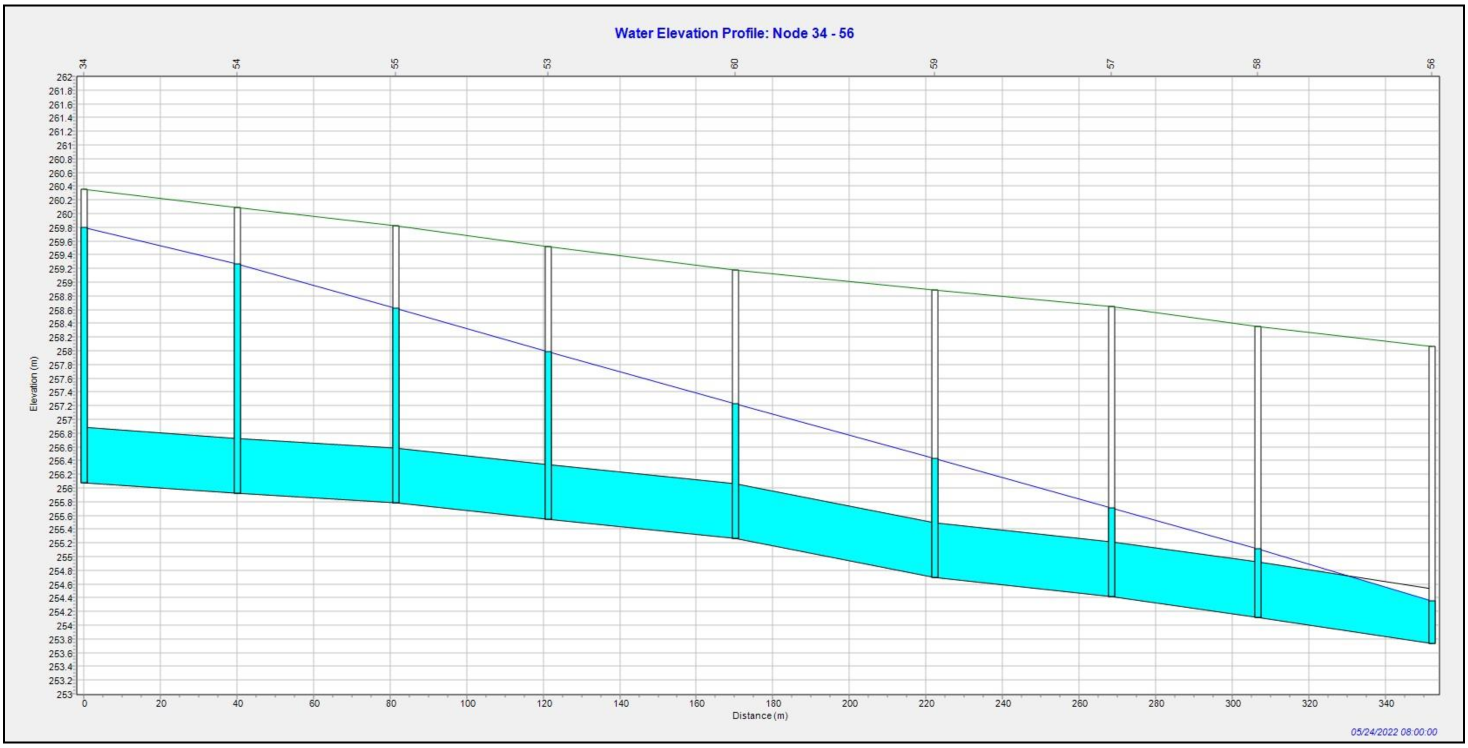
Subcatchment	Total Precip mm	Total Runon mm	Total Evap mm	Total Infil mm	Imperv Runoff mm	Perv Runoff mm	Total Runoff mm	Total Runoff 10^6 ltr	Peak Runoff LPS	Runoff Coeff
93	146.72	0.00	0.00	28.55	0.00	117.95	117.95	8.53	408.35	0.804
96	146.72	0.00	0.00	42.94	0.00	103.65	103.65	4.53	238.39	0.706
97	146.72	0.00	0.00	2.88	124.75	19.13	143.88	3.29	295.52	0.981
98	146.72	0.00	0.00	2.88	124.74	19.13	143.87	4.47	397.23	0.981
99	146.72	0.00	0.00	42.67	0.00	103.98	103.98	2.64	165.00	0.709
100	146.72	0.00	0.00	2.88	124.72	19.12	143.84	10.46	871.32	0.980
101	146.72	0.00	0.00	2.88	124.74	19.13	143.86	5.87	513.90	0.981
102	146.72	0.00	0.00	2.88	124.75	19.13	143.88	3.24	290.49	0.981
103	146.72	0.00	0.00	2.88	124.74	19.13	143.86	5.73	502.05	0.981
104	146.72	0.00	0.00	2.88	124.72	19.12	143.84	10.59	880.87	0.980
105	146.72	0.00	0.00	2.88	124.72	19.12	143.83	12.77	1038.36	0.980
106	146.72	0.00	0.00	2.21	72.86	73.18	78.10	5.92	257.78	0.532
107	146.72	0.00	0.00	2.75	95.80	35.10	108.49	4.93	383.54	0.739
108	146.72	0.00	0.00	2.06	57.51	63.50	67.61	1.80	95.78	0.461
109	146.72	0.00	0.00	38.52	22.73	55.83	58.14	2.99	171.26	0.396
111	146.72	0.00	0.00	28.24	35.51	68.56	94.84	3.85	277.74	0.646
148	146.72	0.00	0.00	1.99	79.87	0.00	89.72	1.35	85.50	0.612
149	146.72	0.00	0.00	1.45	97.10	50.88	103.18	3.54	233.71	0.703

Table (4-19). Outfall details.

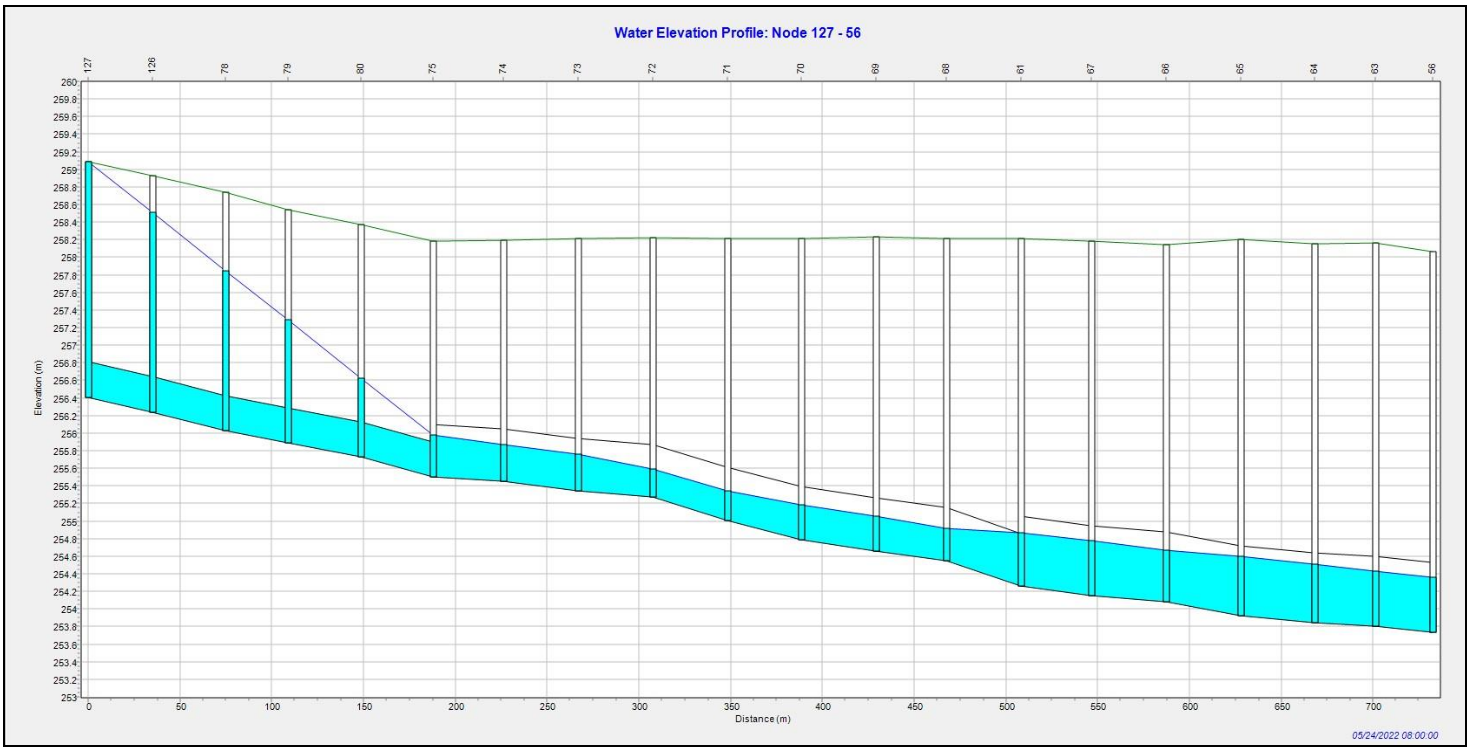
Outfall Node	Flow Freq. Pcnt.	Avg. Flow LPS	Max. Flow LPS	Total Volume 10^6 ltr
112	91.27	25.04	277.74	3.850
146	99.96	1205.02	2781.26	203.259
147	99.73	2501.66	3244.57	420.063

Table (4-20). Node flooding.

Node	Hours Flooded	Maximum Rate LPS	Day of Maximum Flooding	Hour of Maximum Flooding	Total Flood Volume 10^6 ltr	Maximum Ponded Depth Meters
7	0.01	20.21	0	07:41	0.000	0.000
12	0.01	6.28	0	07:44	0.000	0.000
15	0.01	99.85	0	07:44	0.000	0.000
23	0.44	542.80	0	08:00	0.364	0.000
24	0.01	1.55	0	07:41	0.000	0.000
27	0.71	285.01	0	07:55	0.557	0.000
31	0.01	0.06	0	07:41	0.000	0.000
45	0.33	365.69	0	08:00	0.212	0.000
46	0.37	26.84	0	08:00	0.033	0.000
47	0.49	0.56	0	07:41	0.001	0.000
49	0.01	0.03	0	07:47	0.000	0.000
51	0.86	10.49	0	08:05	0.030	0.000
77	2.27	390.85	0	08:00	1.546	0.000
84	0.01	1.08	0	07:56	0.000	0.000
4	0.01	39.91	0	07:44	0.000	0.000
25	0.01	0.67	0	07:41	0.000	0.000
35	0.49	62.45	0	07:58	0.093	0.000
36	0.78	208.27	0	08:05	0.468	0.000
14	0.01	6.42	0	07:44	0.000	0.000
86	0.45	222.93	0	08:00	0.156	0.000
92	0.71	447.92	0	08:00	0.513	0.000
85	0.17	97.18	0	08:00	0.030	0.000
37	1.72	804.19	0	08:00	1.390	0.000
33	0.74	353.19	0	08:00	0.399	0.000
16	0.01	55.07	0	07:44	0.000	0.000
1	0.01	17.27	0	07:41	0.000	0.000
127	0.12	28.60	0	08:00	0.006	0.000



(A)



(B)

Figure (4-27). Water elevation profile of A) 34-56 at 8:00 am; B) 127-56 at 8:00 am.

4.3.2.4. Recorded Rainfall

Similar to the previous scenarios, all LID controllers were used, with the precipitation data used being the only difference. This implementation had two main goals: **first**, to evaluate each LID controller's effectiveness individually within the assigned section; and **second**, to determine the group's influence in directing and controlling runoff at the critical situation (i.e., at 21:00, Figure 4-28). This analytical study focused particularly on the RR allowed a deeper investigation within this given subgroup. After an extensive evaluation based on RR data, the quantitative components of this study are concisely outlined in the tables that will be discussed in the following sections (Tables 4-21 to 23). The spatial coverage of each type of LID controller is summarised in this table, which also offers information on the treatment's proportionate extent concerning an entire area.

This exhaustive investigation employs a passive construction approach to clarify the interactions and contributions of the diverse LID controllers in the circumstances of mitigating runoff within this section.

Figure (4-28). Sub-catchments at 21:00.

In this section, a comprehensive analysis was carried out in seven sub-catchments that include Low Impact Development (LID) controllers. The ongoing tables offer continuous insights to enable a direct comparison of the peak runoff in these sub-catchments with that observed in earlier scenarios. The results vividly demonstrate a considerable reduction in peak runoff. For example, sub-catchment number 111, under scenarios_00 and_01, displayed a peak runoff of 134.12 litres per second. Remarkably, in the current scenario, this peak runoff underwent a significant decrease to 64.85 litres per second, marking a 50% reduction. This significant decrease serves as evidence of the success of the applied LID controllers in mitigating peak runoff, demonstrating a notable enhancement compared to the previous scenarios.

Table (4-21). Sub-catchment details.

Subcatchment	Total Precip mm	Total Runon mm	Total Evap mm	Total Infil mm	Imperv Runoff mm	Perv Runoff mm	Total Runoff mm	Total Runoff 10^6 ltr	Peak Runoff LPS	Runoff Coeff
93	125.40	0.00	0.00	27.17	0.00	97.86	97.86	7.08	136.14	0.780
96	125.40	0.00	0.00	40.41	0.00	84.78	84.78	3.70	76.31	0.676
97	125.40	0.00	0.00	2.82	106.58	15.99	122.57	2.81	53.04	0.977
98	125.40	0.00	0.00	2.82	106.58	15.99	122.56	3.81	72.02	0.977
99	125.40	0.00	0.00	40.39	0.00	84.89	84.89	2.16	46.09	0.677
100	125.40	0.00	0.00	2.82	106.56	15.98	122.55	8.91	168.12	0.977
101	125.40	0.00	0.00	2.82	106.57	15.99	122.56	5.00	94.47	0.977
102	125.40	0.00	0.00	2.82	106.58	15.99	122.57	2.76	52.11	0.977
103	125.40	0.00	0.00	2.82	106.57	15.99	122.56	4.88	92.16	0.977
104	125.40	0.00	0.00	2.82	106.56	15.98	122.55	9.02	170.19	0.977
105	125.40	0.00	0.00	2.82	106.56	15.98	122.54	10.88	205.12	0.977
106	125.40	0.00	0.00	1.93	62.25	47.05	57.96	4.39	106.81	0.462
107	125.40	0.00	0.00	2.36	81.85	24.70	88.25	4.01	95.32	0.704
108	125.40	0.00	0.00	1.94	49.14	33.89	46.23	1.23	43.75	0.369
109	125.40	0.00	0.00	35.36	19.42	43.85	46.75	2.41	49.16	0.373
111	125.40	0.00	0.00	26.67	30.34	55.98	78.79	3.20	64.85	0.628
148	125.40	0.00	0.00	1.72	68.25	0.00	68.69	1.04	24.45	0.548
149	125.40	0.00	0.00	1.27	82.96	35.33	82.09	2.82	56.69	0.655

Table (4-22). Outfall details.

Outfall Node	Flow Freq. Pcnt.	Avg. Flow LPS	Max. Flow LPS	Total Volume 10^6 ltr
112	93.99	20.21	64.85	3.199
146	99.96	1165.69	1938.90	196.640
147	99.73	2481.71	2696.49	416.713

Table (4-23). Node flooding.

Node	Hours Flooded	Maximum Rate LPS	Day of Maximum Flooding	Hour of Maximum Flooding	Total Flood Volume 10^6 ltr	Maximum Ponded Depth Meters
52	0.01	2.64	0	20:07	0.000	0.000
77	0.01	4.82	0	20:08	0.000	0.000
37	0.01	2.62	0	20:07	0.000	0.000

Chapter 5.

Discussion

5.1. Introduction

In the previous sections, the flooding control of the region due to the natural-based solution has been regarded as the main hydraulic-related issue of VR that should be addressed as soon as possible. Concluded based on the obtained results after implementing different scenarios and considering two sets of precipitation data, it was realized that surface runoff is a serious challenge in the region that needs to be addressed urgently to avoid future natural disasters. It was also figured out that the expansion of Druento's channel may play an important role in controlling the surface runoffs. However, a backflow was observed in the water pathways that were supposed to be used to connect the sewer system to the mentioned channel in a way that their functions were totally disturbed. Additionally, in the third scenario, it was tried to apply the LID practices to identify the role of each controller in managing the surface runoffs as well as their individual and cross-effects across the studied area.

In light of the last scenario's results and considering three different alternatives, the economic feasibility of each LID controller was studied. For this section, three scenarios are considered to prepare the capital cost estimations based on the Equations (5-1 to 4).

A= Green roofs surface area × 100 Euros/m^2 Equation (5-1)

B= Excavation surface area × 60 Euros/m^2 Equation (5-2)

C= Excavation length × 100 Euros/m Equation (5-3)

Total 1= A+B+C Equation (5-4)

Where A is the green roof capital cost, B is the costs of pond, channel, and permeable pavement and C is the costs required to implement conduits. All the costs are in Euros. Moreover, the costs related to the unwanted expenses are regarded as general expenses, which are calculated via Equation (5-5). Furthermore, the total required executive costs (Total 2) are calculated via summation of Total 1 and General expenses (Equation 5-6). Ultimately, after applying 22% of Taxes (VAT) the on total required executive costs, the final capital costs are obtained (Equation 5-7).

General expenses= 0.15 x Total 1 Equation (5-5)

Total 2= Total1 + General expenses Equation (5-6)

Total amount= Total 2 + VAT Equation (5-7)

Table (5-1). Cost estimation.

Block	Total Area (ha)	Green Roof Area (ha)	Permeable Pavement (ha)	Rain Garden (ha)	Bio-Retention cell (ha)	Channel and conduits (m)	Total cost (£)
106	7.58	2.15	0.63	0.13	0.30	*N/A	2,775,000.00
107	4.54	0.77	0.50	N/A	0.20	N/A	1,188,000.00
108	**2.66**	**1.08**	**0.06**	**0.06**	N/A	N/A	**1,145,800.00**
109	5.15	0.26	N/A	0.98	N/A	N/A	754,000.00
111	**4.06**	N/A	N/A	**0.40**	N/A	N/A	**200,000.00**
148	1.51	0.41	0.14	N/A	0.03	N/A	508,200.00
149	3.43	0.69	0.20	0.02	0.05	N/A	846,500.00
Druento + conduits	N/A	N/A	N/A	N/A	N/A	**3468.00**	**346,800.00**
Unit Cost (€/u.m.)		100.00	60.00	50.00	60.00	100.00	

*N/A: Not applicable.

Table (5-2) shows the calculated costs based on the derived Equations (5-1 to 5-7). From the outset, it has been tried to consider 80 per cent of the roof as a green roof area (Figure 5-1) due to the high efficiency of the green roof among the other LID controllers and the estimation of the costs for this implementation while considering the various LID controllers is €10,893,312.90. Notably, the cost of the green roof without considering tax and general expenses is €5,360,000which is roughly half of the total expenses for the implementation. Due to this fact, there has been an effort to explore alternative solutions that could be more cost-effective and executable.

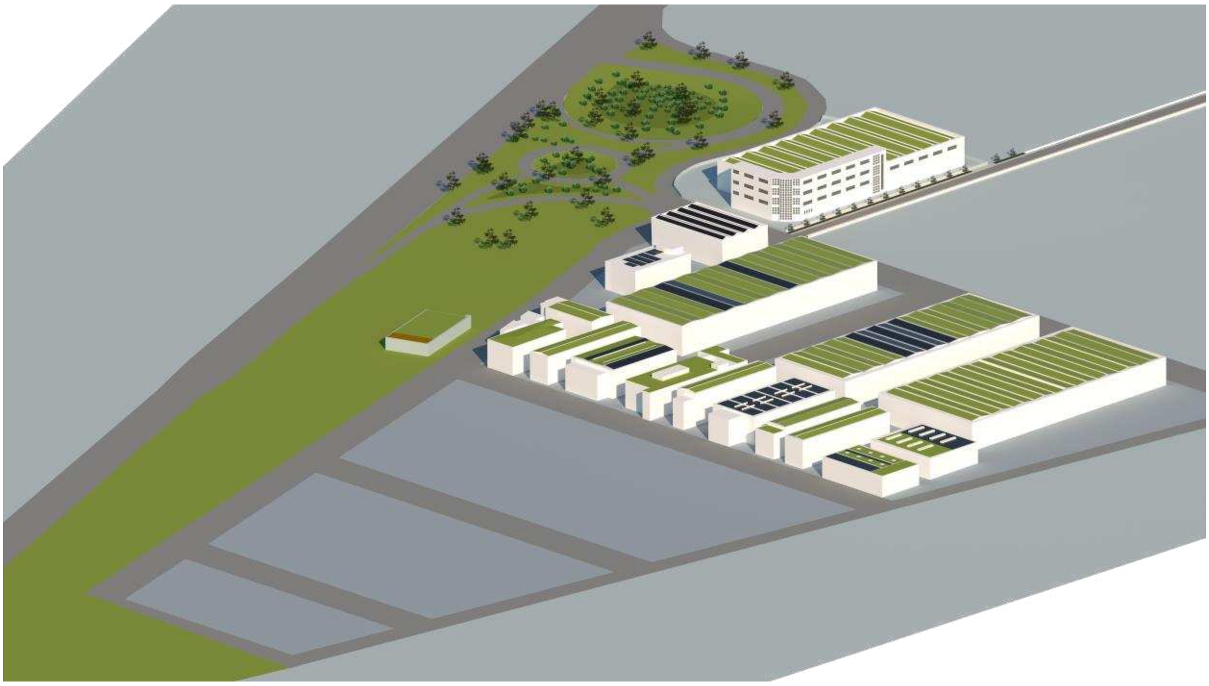


Figure (5-1). 3D model of 80 per cent coverage of roof by green roof.

Table (5-2). Considering 80 per cent of the roof for the green roof

Items	Costs
TOTAL 1	7,764,300.00
General expenses	1,164,645.00
Total 2	8,928,945.00
VAT	1,964,367.90
Total Costs	10,893,312.90

The obtained data in the previous section was recalculated for the sub-catchments and channels in the studied region that required urgent action (Table 5-3). In other words, the focal point of attention was later on the bolded sections of this urban area, which means this part of the city needs crucial attention and should be put in priority (according to the observation witnesses, municipality of VR). By this alternative, the sub-catchments considered in the estimation are 108, 111, and Druento's channel (Figure 5-2) based on the previous analysis driven by the result chapter. The project cost for this section factoring in 80 per cent coverage of the green roof and incorporating all applied LID controllers, is €2,374,717.80.

Figure (5-2). 3D model for the areas related to the Bold Cost.

Table (5-3). Cost estimation for Bold Cost.

Items	Costs (€)
"BOLD" COSTS	1,692,600.00
General expenses	253,890.00
Total 2	1,946,490.00
VAT	428,227.80
Total	2,374,717.80

Due to the high expense of the green roofs, which relates to the private stakeholders, the implication of green roofs in 40% of the available roofs (Figure 5-3) was considered as another practical alternative with lower capital costs. With this adjustment, a significant decrease in total expenses from €10,893,312.90 to €6,381,264.90 was observed marking a reduction of 1.7 times (Table 5-4&5).

Figure (5-3). 3D model of the 40 per cent coverage of roof by green roof.

Table (5-4). Cost estimation.

Block	Total Area (ha)	Green Roof Area (ha)	Permeable Pavement (ha)	Rain Garden (ha)	Bio-Retention cell (ha)	Channel and conduits (m)	Total cost (€)
106	7.58	0.86	**0.63**	0.13	0.30	N/A	1,483,800.00
107	4.54	0.31	0.50	N/A	0.20	N/A	727,200.00
108	**2.66**	**0.43**	**0.06**	**0.06**	N/A	N/A	**497,800.00**
109	5.15	0.11	N/A	0.98	N/A	N/A	595,600.00
111	**4.06**	N/A	N/A	**0.40**	N/A	N/A	**200,000.00**
148	1.51	0.16	0.14	N/A	0.03	N/A	263,400.00
149	3.43	0.28	0.20	0.02	0.05	N/A	433,700.00
Druento + conduits	N/A	N/A	N/A	N/A	N/A	**3468.00**	**346,800.00**
Unit Cost (€/u.m.)		**100.00**	**60.00**	**50.00**	**60.00**	**100.00**	

Table (5-5). Considering 40 per cent of the roof for the green roof

Items	Costs (€)
40% of roof	4,548,300.00
General expenses	682,245.00
Total 2	5,230,545.00
VAT	1,150,719.90
Total	6,381,264.90

The rationale behind this thesis in this section struggled to install the green roof is its superior efficiency in order to the other types of LID controllers as evidenced by the data presented in the following Table (5-6), charts and diagrams according to the Design Rainfall data.

Table (5-6). Scienario_00 and_01 DR

Block	Runoff (MM)	Peak Runoff (LPS)
106	143.81	1650.54
107	143.83	1169.63
108	138.86	649.37
109	80.11	282.81
111	102.99	367.94
148	143.86	478.23
149	143.84	863.87

Figure (5-1) vividly illustrates the significant decrease in the amount of peak runoff of each sub-catchment because of the LID controllers as a comparison with Scenario 00 and 01. For instance, peak runoff in sub-catchment 106 was 1650.54 LPS and after the implementation of LID controllers, it decreased to 233.71 LPS (Table 5-7), representing 7.06 times less than the current situation. Furthermore, after analysing the removal of the green roof, according to the analysis of Scenario 02, the sub-catchment 106 is experiencing an amplifying of peak runoff from 233.71 to 697.85 LPS. This sub-catchment by itself illustrates how much it is worth to consider and execute the green roof. It is remarkable to mention that sub-catchment 111 has no change due to the fact there is no green roof applied and the only implemented LID controller is the rain garden which has been analysed further below.

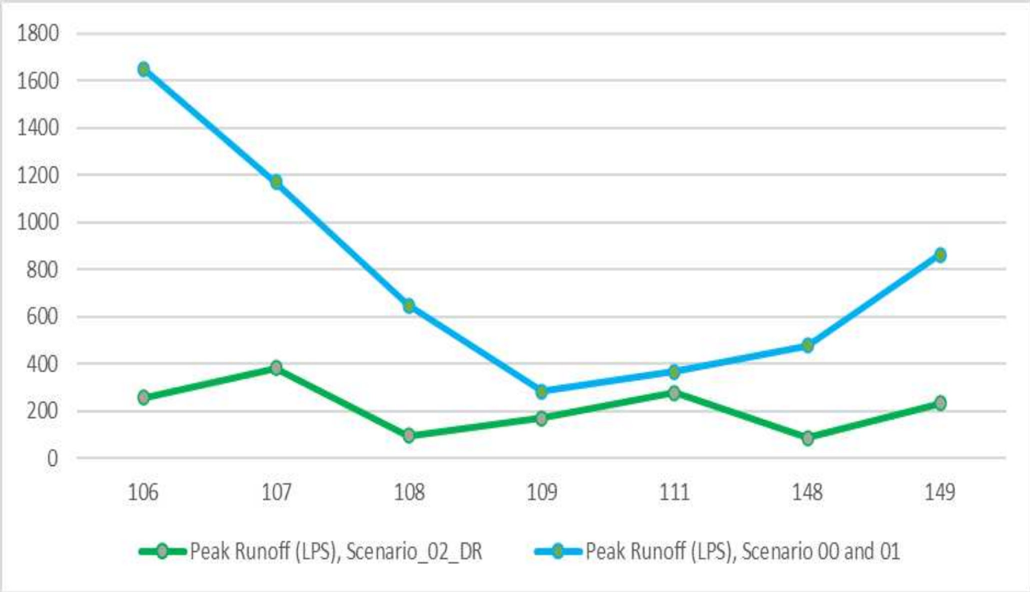


Figure (5-4). Peak runoff comparison.

Table (5-7). Scienario_02 DR

Block	Runoff (MM)	Peak Runoff (LPS)
106	78.1	257.78
107	108.48	383.54
108	67.61	95.78
109	58.14	171.26
111	94.84	277.74
148	89.72	85.5
149	103.18	233.71

Based on the analysis and outcomes driven by Figures (5-2 to 5) and Tables (5-8 to 11), it is evident that the most effective LID controllers in this area of VR consequently are green roofs, rain gardens, permeable pavements, and bio-retention cells. For instance, the sub-catchment 106 (because all the types of LID controllers are applied), the peak runoff for this sub-catchment without green roofs, rain gardens, bio-retention cells, and permeable pavements (each of them is separately removed) are respectively 697.85, 287.73, 297.73, and 337.94 LPS and all of them are higher than the peak runoff of this sub-catchment, 257.78

LPS, when all of the LID controllers are applied. Furthermore, the analysis indicates that if the green roof is not considered, it increases the peak runoff by up to 75.4%, the rain garden by 12.22%, permeable pavement by 5.47%, and bio-retention cell leads to a 5.14% increase.

Table (5-8). Scenario_02_DR without the green roof.

Block	Runoff (MM)	Peak Runoff (LPS)
106	123.09	697.85
107	132.18	544.11
108	133.76	301.88
109	64.5	218.15
111	94.84	277.74
148	135.7	188.38
149	136.91	412.33

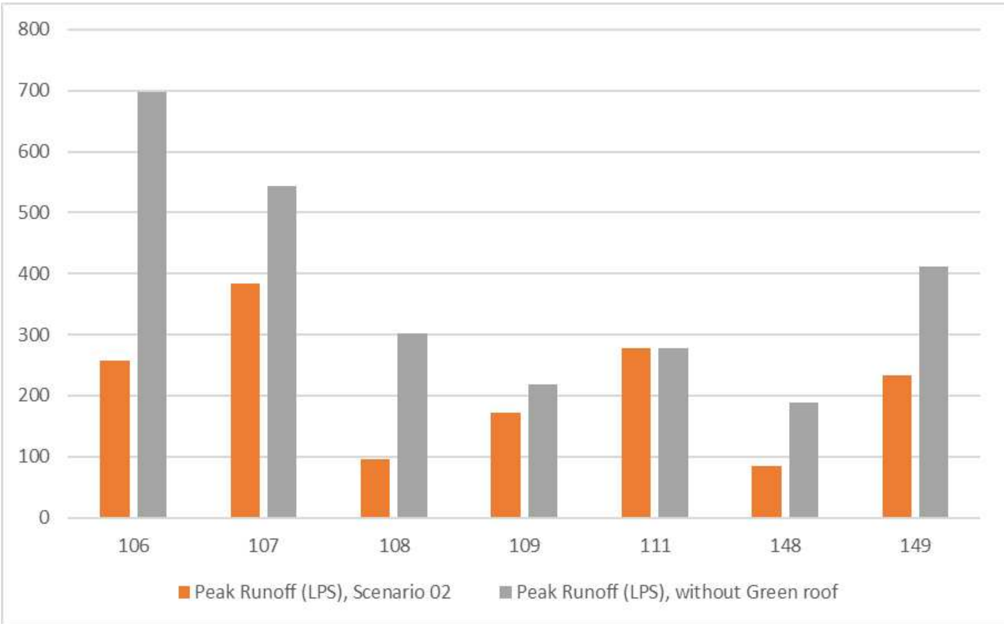


Figure (5-5). Sub-catchments without green roof.

Table (5-9). Scenario_02_DR without rain garden.

Block	Runoff (MM)	Peak Runoff (LPS)
106	84.25	287.73
107	108.49	383.54
108	75.68	116.54
109	89.45	241.21
111	115.4	327.66
148	89.72	85.5
149	104.96	247.12

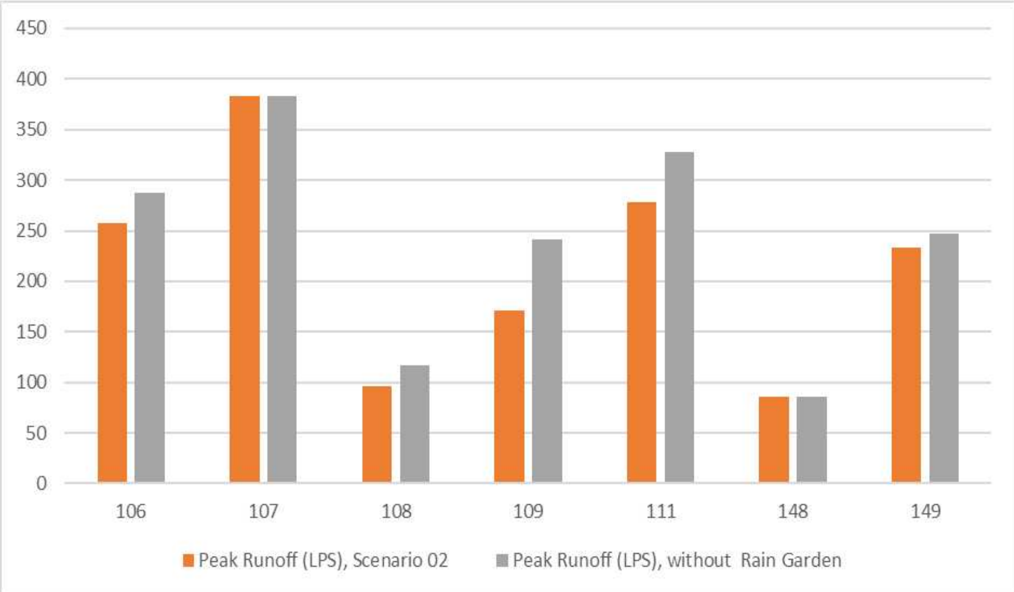


Figure (5-6). Sub-catchments without rain garden

Table (5-10). Scenario_02_DR without bio-retention cell

Block	Runoff (MM)	Peak Runoff (LPS)
106	86.82	297.73
107	116.51	407.68
108	67.61	95.78
109	58.14	171.26
111	94.84	277.74
148	93.87	89.89

149	106.74	242.69

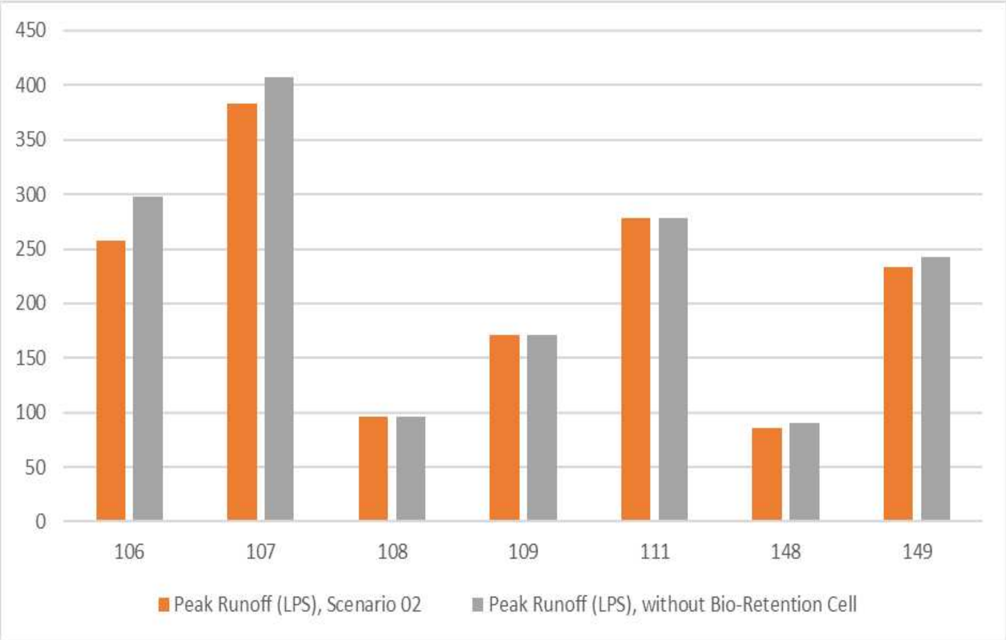


Figure (5-7). Sub-catchments without bio-retention cell

Table (5-11). Scenario_02_DR without permeable pavement

Block	Runoff (MM)	Peak Runoff (LPS)
106	83.49	337.94
107	115.7	379.42
108	68.94	101.65
109	58.14	171.26
111	94.84	277.74
148	95.31	81.74
149	106.7	237.94

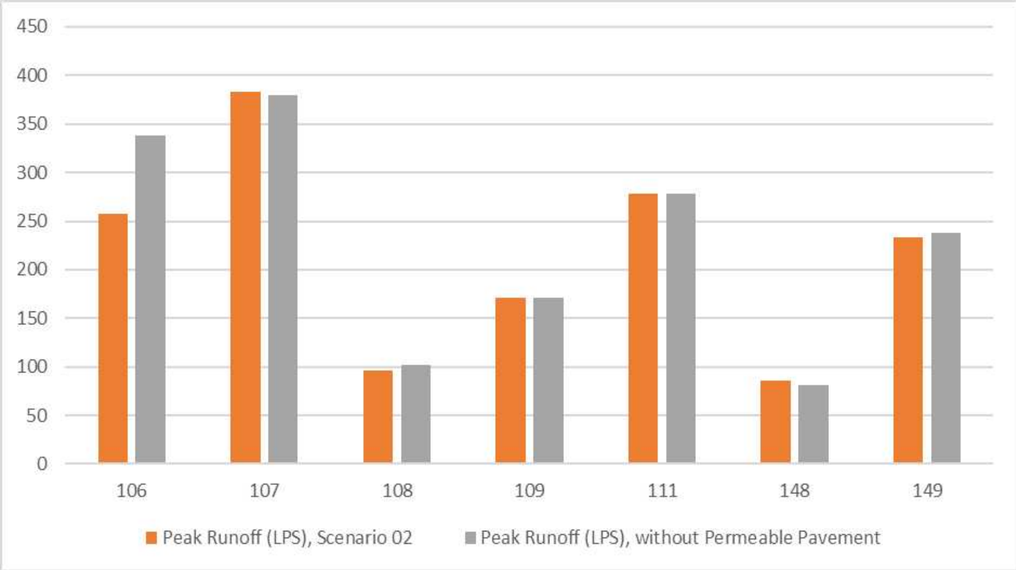


Figure (5-8). Sub-catchments without permeable pavement.

The following analyses and calculations have been done for Scenario_02 with the data from RR and outcomes accompanying Figure (5-6) and tables (5-12 & 13).

Table (5-12). Scenario_02 RR

Block	Runoff (MM)	Peak Runoff (LPS)
106	57.96	106.81
107	88.25	95.32
108	46.23	43.75
109	46.75	49.16
111	78.79	64.85
148	68.69	24.45
149	82.09	56.69

Table (5-13). Scenario 00 and 01_RR

Block	Runoff (MM)	Peak Runoff (LPS)
106	122.47	354.39
107	122.51	235.34
108	117.74	126.2
109	64.49	121.36
111	84.12	134.12
148	122.55	87.53
149	122.53	166.51

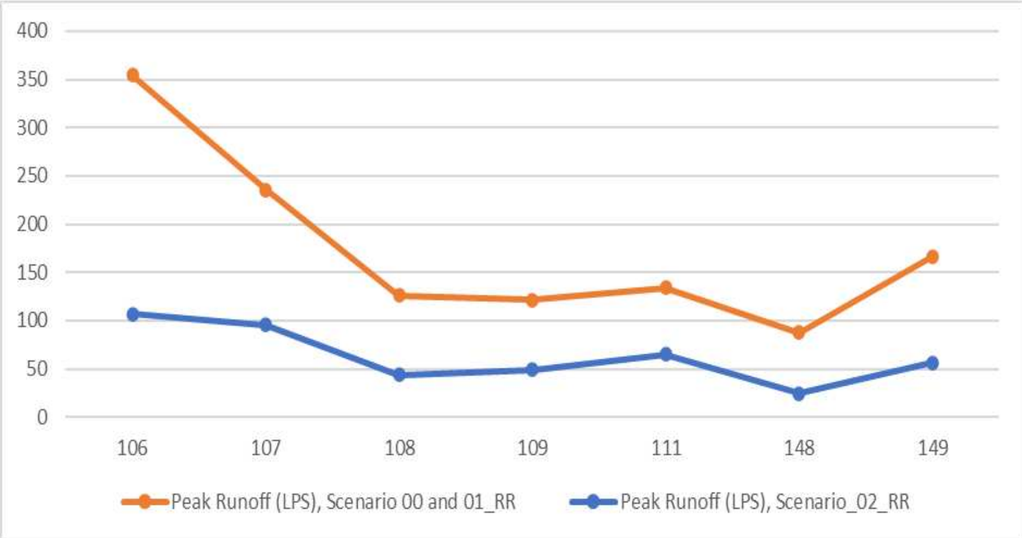


Figure (5-9). Peak runoff comparison.

Similar to the analysis that has been conducted for the section by the data of DR, the outcomes for the data of RR reveal a decrease in all the sub-catchments. For instance, the peak runoff of sub-catchment 106 decreased 3.32 times (from 354.39 to 106.81 LPS) less than in the previous scenarios where LID controllers were not applied.

After dismissing the green roof from the section, the analysis demonstrates the amplifying of peak runoff in each of those sub-catchments that had green roofs. For example, the peak runoff for sub-catchment 106 increases from 106.81 to 141.21 LPS and it indicates the positive impact of green roofs in reducing the peak runoff as shown in Table (5-14) and Figure (5-7).

Table (5-14). Scenario_02_RR without the green roof

Block	Runoff (MM)	Peak Runoff (LPS)
106	103.27	141.21
107	111.84	99.69
108	112.47	54.46
109	53.01	55.12
111	78.79	64.85
148	114.96	33.78
149	116.07	77.33

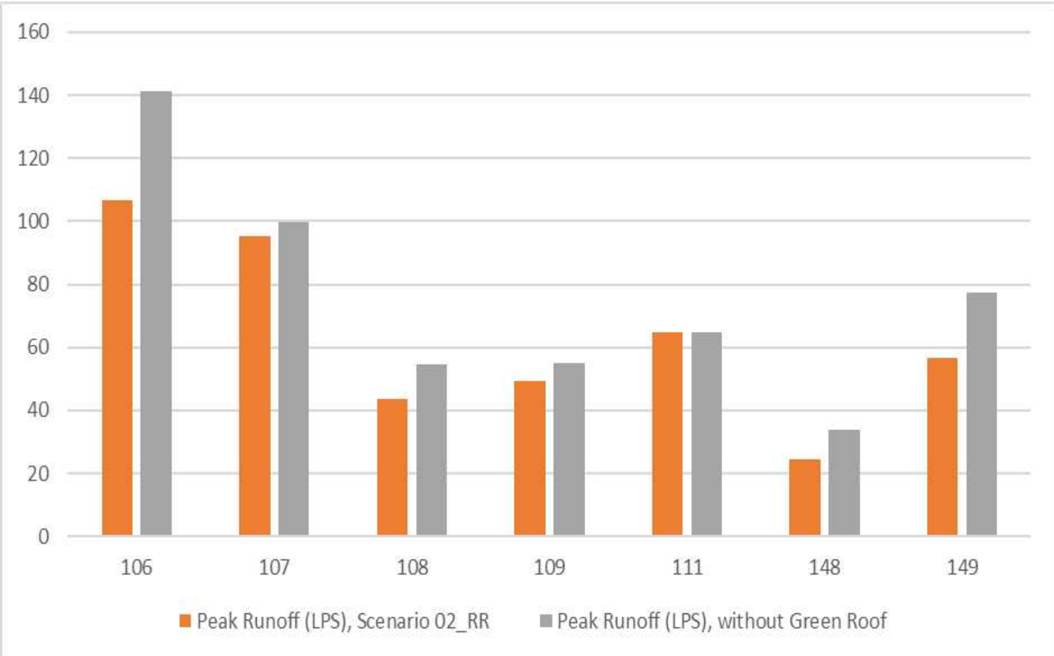


Figure (5-10). Sub-catchments without green roof

According to the analysis and outcomes from Figures (5-8 to 10) and Tables (5-15 to 17), although the results for the RR data demonstrate the same result as the DR data in the aspect of reducing the peak runoff of each LID controller, the effectiveness of each LID controller varies based on the percentage of amplification brush off of each, respectively is green roof by 19.36%, rain garden by 12.99%, bio-retention cell by 3.88%, and in the end permeable pavement 2.26%. These percentages highlight the individual contributions of each LID controller to peak runoff reduction in the studied area.

Table (5-15). Scenario_02_RR without rain garden

Block	Runoff (MM)	Peak Runoff (LPS)
106	57.96	106.81
107	88.25	95.32
108	54.18	44.11
109	72.02	79.34
111	95.75	78.83
148	68.69	34.45
149	83.84	59.48

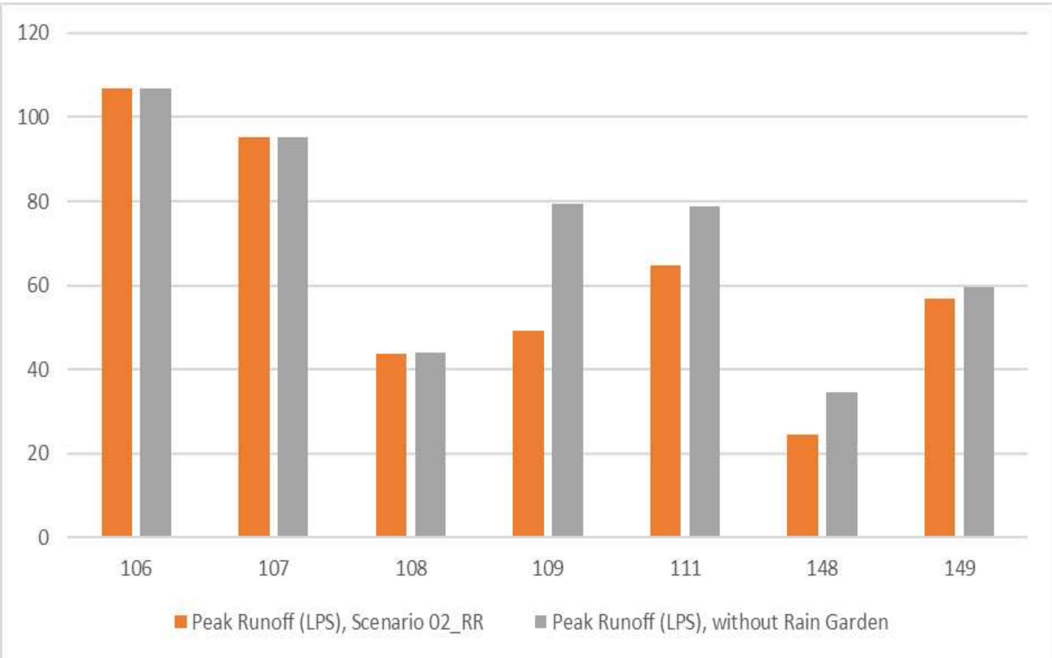


Figure (5-11). Sub-catchments without rain garden.

Table (5-16). Scenario_02_RR without bio-retention cell

Block	Runoff (MM)	Peak Runoff (LPS)
106	65.36	114.86
107	94.84	102.08
108	46.23	43.75
109	46.75	49.16
111	78.79	64.85
148	72.22	25.24
149	85.12	58.23

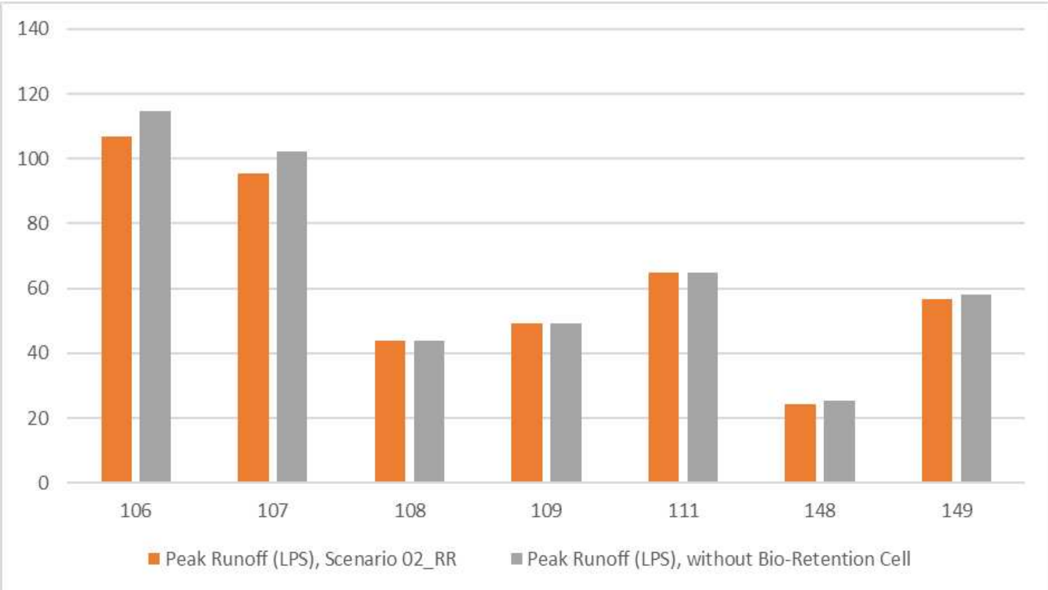


Figure (5-12). Sub-catchments without bio-retention cells.

Table (5-17). Scenario_02_RR Without Permeable Pavement

Block	Runoff (MM)	Peak Runoff (LPS)
106	63.45	111.15
107	95.36	96.66
108	47.61	43.77
109	46.75	49.16
111	78.79	64.85
148	74.33	24.68
149	85.68	60.74

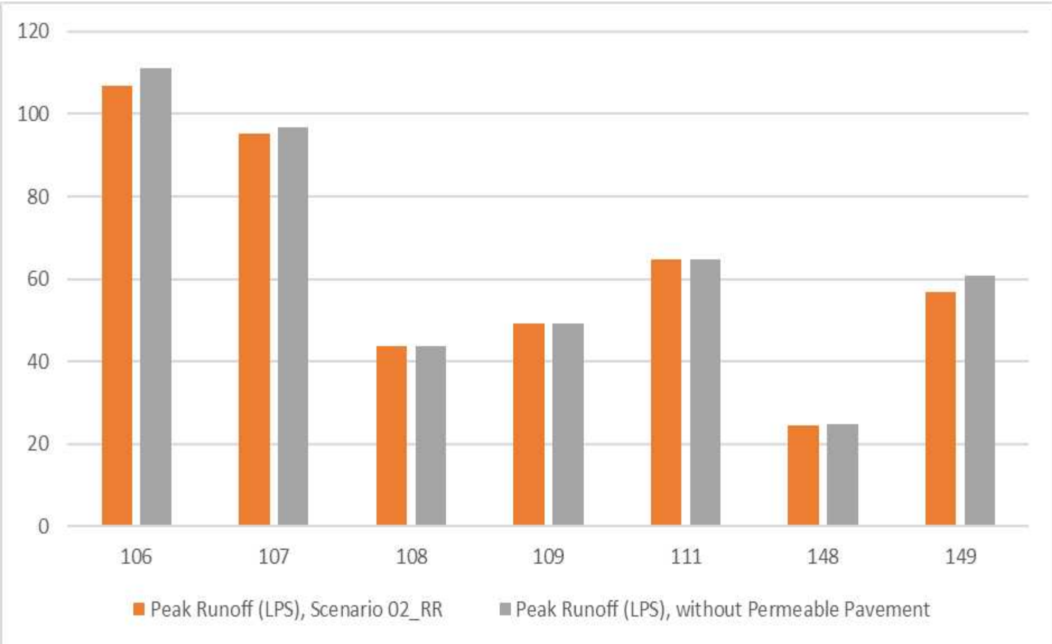


Figure (5-13). Sub-catchments without permeable pavement

Chapter 6.

Conclusion

Throughout the outcomes of the result and discussion chapters, it is understandable that the rainfalls, both the DR and RR, are the cause of flooding according to the imperviousness of the area. To overcome this issue there were two main solutions, **first**, modifying the Druento Channel and connecting some paths from the sewer system to this channel, and **second**, the usage of LID controllers in the case study.

Due to the first alternative, it is understandable that the modification of the Druento channel, both the dimension of the channel and the natural base solution of it, is entirely eliminating the flooding of the mentioned channel but the paths are not functional because of reverse function. On the other hand, the last scenario illustrates that Low Impact Development (LID) controllers would be a good solution to decreasing the runoff of the case study. The obtained results based on DR data indicated that the peak runoffs increased up to 75.4%, 12.22%, 5.47%, and 5.14% after avoiding the application of the influences of green roof, rain garden, permeable pavement, and the bio-retention cell, respectively. Moreover, the results within RR data showed that dismissing the green roofs led to an increase in the peak runoff by 19.36%, while that for rain gardens, bio-retention cells, and permeable pavement were 12.99%, 3.88%, and 2.26% increase, respectively.

Furthermore, according to the economic estimation of the case study, as mentioned in the previous chapter, there are three alternatives to implementing this study to reduce the impact of natural hazards. The first solution which includes the full application of the project, costs **€10,893,312.90**, the second one which is known as the bold cost is just for the implementation of the most priority intervention of the area, costs **€2,374,717.80**, and the last considers just 40% of the green roof coverage of the roofs, because the majority of the costs are related to this section (that is related to the private sector), costs **€6,381,264.90**. Noteworthy, most of the prices are related to the private sector.

It is necessary to emphasise that all the mentioned goals of agenda SDGs that were in common with the Life Project are entirely covered, throughout this thesis analysis and the lack of green areas is the main cause of flooding in the case study has been solved. On the other hand, it should not underestimate the role of the Municipality of VR and the Metropolitan City of Turin in applying this project the territorial governance of the Piedmont region is an important challenge because of the money constraints, this was rather than the limitation of the collecting the data and comparing with the similar studies.

This project also opens a new gate to the future of developing resilient cities, sponge cities by the effects of Low Impact Development (LID), and also finding the solution of the territorial governance of Piedmont to grant some budgets for such a project. Moreover, this study includes certain sections, such as sub-catchment number 111, to establish water storage facilities. These facilities serve not only for flood control but also with the aim of replenishing the underground aquifers. On the other hand, to fill the gap in the budget for the private stakeholders, there could be some incentives to encourage private stakeholders, such as the National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) that provides Super Eco bonus 110, for implementing the necessary LID practices in the region.

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