Republic of Iraq

Ministry of Higher Education & Scientific Research

University of Kerbala

College of Engineering

Civil Engineering Department

Simulation of Storm Network by Using EPA SWMM Program in Un–urban Catchment Area in Karbala City

A Thesis Submitted to the Council of the Faculty of the College of the Engineering/University Of Kerbala in Partial Fulfillment of the Requirements for the Master Degree in Infrastructure Engineering

By:

Zahraa Sabri Waheed

Supervisors

Asst. Prof. Dr. Haider H. Alwan

Prof. Dr. Waqed H. Hassan

January 2025 Shaban 1446

بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

وَمَا يَعْلَمُ تَأْوِيلَهُ إِلَّا اللَّهُ وَالرَّاسِخُونَ فِي

الْعِلْمِ يَقُولُونَ آمَنَّا بِهِ كُلٌّ مِنْ عِنْدِ رَبِّنَا

صدق الله العظيم

(آل عمران: الاية 7)

Examination committee certification

We certify that we have read the thesis entitled **"Simulation of Storm Network by Using EPA SWMM Program in Un–urban Catchment Area in Karbala City "**and as an examining committee, we examined the student **"Zahraa Sabri Waheed"** in its content, and in what is connected with it and that, in our opinion, it is adequate as a thesis for the degree of Master of Science in Civil Engineering.

Supervisor
Signature:
Name:.Asst.Prof. Dr. Hayder Hussein Alwan Algretawee
Date: / / 2025

Supervisor
Signature:
Name :. Prof. Dr. Waqed H. Hassan
Date: / / 2025

Member
Signature:
Name :.Asst. Prof.Dr.Maad F.Hussian
Date: 5 / 5 / 2025

Member
Signature:
Name :.Asst.Prof.Dr.Amer Hassan Taher
Date: / / 2025

Chairman
Signature:
Name :. Prof. Dr. Musa H. Al-Shammari
Date: / / 2025

Signature:
Name:Asst. Prof.Dr.Aysar Tuama Al-Awadi
Head of the Department of Civil Engineering
Date: / / 2025

Signature:
Name:Prof.Dr.Haider Nadhom Azziz
Dean of the Engineering College
Date: / / 2025

CamScanner الممسوحة ضوئيا بـ

Supervisor certificate

We certify that the thesis entitled **"Simulation of Storm Network by Using EPA SWMM Program in Un–urban Catchment Area in Karbala City "** was prepared by **Zahraa Sabri Waheed** under our supervision at the Department of Civil Engineering, Faculty of Engineering, University of Kerbala as a partial of the fulfilment of the requirements for the Degree of Master of Science in Civil Engineering.

Signature:

Asst. Prof. Dr.Hayder Hussein Alwan Algretawee

Date: / / 2025

Signature: Waqed H.H

Prof. Dr. Waqed H. Hassan

Date: / / 2025

CamScanner الممسوحة ضوئيا بـ

Linguistic certificate

I certify that the thesis entitled **"Simulation of Storm Network by Using EPA SWMM Program in Un–urban Catchment Area in Karbala City "** which has been submitted by **Zahraa Sabri Waheed** has been proofread, and its language has been amended to meet the English style.

Signature:

Dr.Awad Ali Sagheer Jadooe

Date: / / 2025

CamScanner الممسوحة ضوئيا بـ

Undertaking

I certify that the research work titled **"Simulation of Storm Network by Using EPA SWMM Program in Un–urban Catchment Area in Karbala City "** is my own work. The work has not been presented elsewhere for assessment. Where material has been used from other sources, it has been properly acknowledged/referred.

Signature:

Zahraa Sabri Waheed

Date: / / 2025

CamScanner الممسوحة ضوئيا بـ

Dedication

I dedicate this work

To the Master of the Age and Time, Imam Mahdi (may God hasten his return),

To the one who was my source of encouragement in walking the path of knowledge and supported me in every step

(my father),

To the one who sacrificed her youth so that we could reach the highest ranks and positions

(my mother),

To those who stood by my side in this difficult year and endured all the circumstances I went through, my husband

(Prof. Dr. Ali Karim) and my children (Hussein and Shams),

To those who supported and encouraged me throughout this stage

(my sister and brothers),

To those who assisted me, listened to me, and stood by my side (my friends).

Acknowledgments

First, I want to thank Allah, who gave me the strength, success, and determination to complete this work despite the difficult circumstances I faced.

I would like to express my deep gratitude and appreciation to my supervisors, Prof. Dr. Waqid Hammed Hassan and Assistant Prof. Dr. Haider Hussein Alwan, who made a great effort to guide me throughout the preparation of this thesis, and for their constant encouragement. It is an honor for me to be under their supervision.

I also extend my sincere thanks to the Directorate of Sewerage in Karbala, Department of Geographic Information Systems.

I extend my highest thanks and gratitude to my family, especially my father, husband, sons, and brothers, for their continuous support and encouragement

Finally, I extend my sincere thanks and gratitude to everyone who supported me and provided me with advice and assistance in completing this work.

My sincere respect to all of you

Abstract

Rainfall patterns are affected by climate change in the region, which leads to increased surface runoff and thus flooding the stormwater network in the neighborhood. Most cities have adopted sustainable stormwater management measures and objectives to conserve water resources. Changing climatic conditions and seasonal fluctuations have led to increased rainfall levels and accumulation on sidewalks and roads and their collection inside roads. This study aims to find a modern way to shift from traditional stormwater management methods to more sustainable methods, based on the selection of Karbala city in Iraq, and more precisely, the Al-Wafa neighbourhood located southwest of the city, and relying on collecting historical data (rainfall and network data) to build a simulation model for the stormwater network in the region using the Stormwater Management Model (SWMM) program and studying the impact of floods on the stormwater network in Al-Wafa neighbourhood. The effectiveness of the stormwater network in the region was evaluated before and after rainfall for several recurrence periods of 2, 5, 10, and 20 years. In addition, the model was calibrated after its analysis by adjusting the characteristics of the important sub-basins that were calculated based on the modelled and observed discharges. The flood volume in the network after analysis reached 6921 m^3 in the return period of 2 years and then increased to 9956 m^3 when the return period was extended to 20 years; this is due to climate change and thus led to floods in the rainwater network in the vicinity, which negatively affects the network infrastructure. The flood locations in the network were identified through the program, and appropriate solutions were proposed for this

problem while maintaining the value of the normalized mean square error (NMSE), which reached 1.16 in the return period of 2 years, and the coefficient of determination (R^2) 0.934, while in the return period of 20 years, the normalized mean square error (NMSE) was 0.93 and the coefficient of determination (R^2) 0.899 within the acceptable limits. Three additional drainage lines were proposed for the network, and LID technology was added to achieve sustainability, which led to a decrease in the frequency of floods. Rain gardens are one of the basic methods for complete control of surface water runoff during floods. This method was also applied in the Karbala Al-Wafa area to control the initial floods caused by the rainwater network. The maximum discharge was confirmed by simulating the area before and after adding rain gardens. After simulation, the flood reduction was 10.47%, 19.4%, 15.99%, and 15.46% over the return periods of 2, 5, 10, and 20 years, respectively. The results showed a clear difference in flood reduction. It was observed that the maximum number of flooded manholes during the 2-year return period was 31 manholes without rain gardens, while after adding rain gardens, the number decreased to 14 manholes. This demonstrates the effectiveness of rain gardens in reducing floods.

Table of Contents

Undertaking ..... خطأ! الإشارة المرجعية غير معرّفة.
Dedication v
Acknowledgments vi
Abstract vii
Table of Contents ix
List of Figures xiii
List of Figures in Appendices xvii
List of Tables xviii
List of Abbreviations xx
Chapter One: Introduction 1
1.1 Overview 1
1.2 The importance of stormwater management in urban areas 2
1.3 The role of drainage system simulation in rainwater networks 3
1.4 Environmentally friendly infrastructure 4
1.5 Problem state 5
1.6 Thesis Objective 5
1.7 Scope of the study 6
1.8 Thesis Methodology 7
1.9 Thesis Structure 8
1.10 Limitations 9
Chapter Two: Theory Concept of Literature Review 11
2.1 Floodwater and Surface Runoff 11
2.2 Management of Urban Discharge 12

2.3 Flooding: Causes and Consequences 14
2.4 Urbanization's influence on the natural hydrological cycle 15
2.4.1 The effect of urbanization on discharge 17
2.4.2 Urbanization's influence on water quality 19
2.4.3 Environmental impact on water bodies as a result of urban expansion 20
2.5 Transportation of stormwater discharge 21
2.6 System for Draining Stormwater 22
2.6.1 Flood drainage system jobs 22
2.7 Different types of floodwater drainage systems 22
2.8 Low Impact Development (LID) 24
2.9 Sustainable Urban Stormwater Management: The Role of Low Impact Development (LID) and Bioretention Systems : 26
2.10 Permeable Pavement: A Sustainable Solution for Urban Runoff Management 29
2.11 Low-impact development practices (LIDs) 31
2.12 Modeling-based Assessment of LID 33
2.13 Simulation Studies on Low Impact Developments (LIDs) 34
2.14 Impact of Permeable Pavement and Green Infrastructure on Runoff Management 37
2.15 Bioretention/Rain Garden 39
2.16 Identification of research gaps and the necessity of this study41
2.17 Summary 42
Chapter Three: Methodology 44
3.1 Introduction 44

3.2 Study area.....47
3.3 Data collected.....48
3.3.1 The topographic.....48
3.3.2 Land use.....50
3.3.3 The hydraulic data.....51
3.3.4 Hydrology data.....52
3.3.5 IDF Curves.....53
3.4 Simulation Setup for SWMM.....54
3.4.1 SWMM model.....54
3.4.2 Modeling Hydrology Data.....55
3.5 The Modeling of Hydraulic Data.....72
3.5.1 Pipe characteristics.....72
3.5.2 Manholes.....74
3.5.3 Pump station.....76
3.6 Analysis of Sensitivity.....77
3.7 Calibration and validation.....78
3.8 Low-impact development simulation.....79
Chapter Four: Results and Discussion.....86
4.1 Introduction.....86
4.2 Rainfall intensity modeling.....86
4.2.1 Generating IDF Curves.....86
4.2.2 Selecting rainfall intensity for modeling.....90
4.3 Model calibration and validation.....90
4.4 Climate change's impact on the rainwater drainage system.....96

4.4.1 The quantity of stormwater that flows untreated during damp weather 98
4.4.2 Quantity of stormwater in wet weather flow after adding three pipes to the network 112
4.4.3 The quantity of stormwater that flows during rainy weather for the Low Impact Development (LID) 121
4.5 Summary 133
Chapter Five: Conclusion and Recommendations 135
5.1 Conclusion 135
5.2 Recommendations 136
References 137
Appendix 1

List of Figures

Figure 2-1 shows the effect of urbanization on the natural hydrological cycle.....16

Figure 2-2 Surface runoff is subject to change before and after population development. 19

Figure 2-3 Water transportation before and after urbanization 22

Figure 2-4 Bioretention facility and its hydraulic pattern.....28

Figure 2-5 Representative permeable pavement schematic diagram .30

Figure 2-6 Types of LID 32

Figure 3-1 flowchart working methodology. 46

Figure 3-2 Al-Wafaa neighborhood in Karbala, Iraq.....47

Figure 3-3 Slope Map of Al Wafaa Area Generated by GIS Software Based on DEM.....49

Figure 3-4 The contour map of the study area was created using a geographic information system(GIS) based on digital elevation model data (DEM).....50

Figure 3-5 Al-Wafaa Quarter's land use in Karbala, Iraq. 51

Figure 3-6 Daily rainfall data for Karbala city station for the period (1984 - 2023) 52

Figure 3-7 Subcatchment Areas of the Study Area by Using SWMM 58

Figure 3-8 Width of Study Area Subcatchments by SWMM 60

Figure 3-9 Determine the maximum length of a surface runoff 60

Figure 3-10 The SWMM modeling sub-catchment properties table. .62

Figure 3-11 The SWMM sub catchment segments 63

Figure 3-12 Green ampere factor for each subcatchment. 69

Figure 3-13) propose a nonlinear reservoir model to describe a sub-catchment 70

Figure 3-14 Characteristics of pipes in the rainwater network in the Al-Wafaa Quarters.....74

Figure 3-15 Characteristics of manholes in the rainwater network in Al-Wafaa Quarter's.....76

Figure 3-16 LID of the editor.....81

Figure 3-17 Features of the sub-catchment with the number(39).....84

Figure 3-18 For sub-catchment number 39, the LID usage editor is applicable.....85

Figure 3-19 includes LID controls within sub-catchment number 39. 85

Figure 4-1 The Rainfall IDF curve figure illustrates a diagram derived from statistical data used to determine rainstorm intensity in Kerbala City, Iraq, for 2, 5, 10, and 20 years of rainstorm frequency. 90

Figure 4-2 Using data from 2 years of rainfall, density, and return periods, the SWMM model calculates the coefficient of determination (R^2) between the design and maximal discharge. 92

Figure 4-3 Using data from 5 years of rainfall, density, and return periods, the SWMM model calculates the coefficient of determination (R^2) between the design and maximal discharge. 93

Figure 4-4 Using data from 10 years of rainfall, density, and return..93

Figure 4-5 Using data from 20 years of rainfall, density, and return..94

Figure 4-6 Assessment of the Al-Wafaa Quarter rainwater network before stormwater leaking. 97

Figure 4-7 Al-Wafaa at a two-year return time, the quarterly assessment of the rainwater network is conducted during stormwater leaks. 103

Figure 4-8 Al-Wafaa at a five-year return time, the quarterly assessment of the rainwater network is conducted during stormwater leaks. 104

Figure 4-9 Al-Wafaa at a ten-year return time, the quarterly assessment of the rainwater network is conducted during stormwater leaks. 106

Figure 4-10 Al-Wafaa at a twenty-year return time, the quarterly assessment of the rainwater network is conducted during stormwater leaks. 107

Figure 4-11 water elevation in the manholes 111

Figure 4-12 The rainwater network in the Al-Wafaa neighborhood with proposed solutions to add three additional lines 113

Figure 4-13 The rainwater network in the Al-Wafaa neighbourhood with proposed solutions to add three additional lines at a two-year return period 115

Figure 4-14 The rainwater network in the Al-Wafaa neighborhood with proposed solutions to add three additional lines at a five-year return period 116

Figure 4-15 The rainwater network in the Al-Wafaa neighborhood with proposed solutions to add three additional lines at a ten-year return period 117

Figure 4-16 The rainwater network in the Al-Wafaa neighborhood with proposed solutions to add three additional lines at a twenty-year return period 118

Figure 4-17 Rainwater network in the Al-Wafaa neighborhood after adding LID technology, with a return period of two years, as proposed solutions. 123

Figure 4-18 Rainwater network in the Al-Wafaa neighborhood after adding technology LID with a return period of 5 years as proposed solutions. 124

Figure 4-19 Rainwater network in the Al-Wafaa neighborhood after adding technology LID with a return period of ten years as proposed solutions. 127

Figure 4-20 Rainwater network in the Al-Wafaa neighborhood after adding technology LID with a return period of twenty years as proposed solutions. 128

List of Figures in Appendices

FigureA- 1 Software Interface for SWMM…….……1
FigureA- 2 Rain full intensities at various frequencies for Kerbala City, Iraq……....…….2
Figure A-3 An editor for time series with a return period of 5 years ..3
FigureA- 4 Summary Project……..…….4
FigureA- 5 The "Subcatchment and manholes Properties" input in SWMM……..…….…….….5
FigureA- 6 The "Pipes Properties" input in SWMM…….……..6
FigureA- 7 Water elevation profile: node (HR36AZ-HR40) during Rainfall…….……..…….….7
FigureA- 8 Water elevation profile: node (HR51-HR45) during Rainfall…….……7
FigureA- 9 Enter the technical characteristics of the LID in the SWMM…….……..8
FigureA- 10 Modify the network direction in the program (SSA)….8
FigureA- 11 Drawing blocks in the program (GIS)……...…..……..9

List of Tables

Table 3-1 Land Use Impervious Area Percentage 65

Table 3-2 Roughness Coefficient for Subcatchments for Manning ...66

Table 3-3 Depth of depression storage for various land uses 67

Table 3-4 Variations in Green Ampt parameters for various soil types 68

Table 3-5 The roughness coefficient measured by Manning for the pipelines 73

Table 3-6 Stormwater Systems in the Study Area: Manhole Properties 76

Table 3-7 Parameters of partial .permeability of LID 82

Table 4-1 The intensity of rainfall for four return periods.....88

Table 4-2 The intensity of rainfall (mm/hr) at different frequencies..89

Table 4-3 Calibration of SWMM data with design data.....91

Table 4-4 Impact of precipitation occurrences on Al-Wafaa Quarter MR-44.....99

Table 4-5 The discharge rate of the excess manholes in the network, according to the SWMM modeling 100

Table 4-6 The percentage of the five stages mentioned for flooded manholes. 108

Table 4-7 The percentage of the five stages mentioned for flooded manholes after adding three additional pipes. 119

Table 4-8 The effect of rainfall events on Al-Wafaa Quarter MR-44 by adding three additional lines to the network. 120

Table 4-9 After the three pipelines are added, each return period's phases of inundated manholes 121
Table 4-10 The percentage of the five stages mentioned for flooded manholes with LID. 129
Table 4-11 Rainfall and its impact on the Al-Wafaa neighborhood using technology LID 130
Table 4-12 The flooded manhole phases are included for each return period following the addition of LID. 131

List of Abbreviations

DSK	Directorate Kerbala Sewage
DEM	Digital Elevation Model
EPA	Environmental Protection Agency
GI	Green infrastructure
GIS	Geographic Information System
IDF	Intensity Duration Frequency
LID	Low Impact Development
NMSE	Normalized mean square error
PVC	Polyvinyl Chloride
R	Correlation coefficient
R^2	Determination coefficient
SSA	Storm and Sanitary Analysis
SWMM	Storm Water Management Model
SUDS	Sustainable Urban Drainage Systems
USEPA	U.S.environmental protection agency
UPVC	Un plasticized polyvinyl chloride
WSUD	Water Sensitive Urban Design

Chapter One: Introduction

1.1 Overview

The hazards associated with stormwater flooding have been exacerbated by urbanization and population growth. Urban stormwater discharge has been altered as a result of climate change and a variety of human activities. Urban areas have experienced increased frequency of floods in recent years. The environment is significantly impacted by the improper management of this water and the failure to adhere to design standards, increasing flood problems. Engineers, researchers, decision-makers, and ecosystem specialists face a significant challenge in administering rainwater. The water is collected in the form of lakes after it flows along the side paths of highways and depressions after rain falls. It results in infrastructure damage and floods unless an appropriate evacuation method is discovered. Urban flooding management is one of the challenges that cities are currently confronted with. The urban stormwater systems are experiencing an increasing strain due to urbanization, and changes in urban flooding. This has resulted in environmental issues, infrastructure damage, and a high maintenance cost (Hassan et al., 2017, Hussein et al., 2015).

Environmental and water science researchers and specialists are pursuing the most effective disposal methods. This includes the use of various methods, including modeling and simulation software. EPA SWMM (Stormwater Management Model) and climate change are anticipated to result in a higher frequency of extreme weather phenomena, a decrease in rainfall in certain regions, and an increase in rainfall in others (Pachauri et al., 2014).

Iraq is an extremely vulnerable nation to climate change as a result of both natural and artificial factors. Its economy is significantly dependent on oil revenues, contributing to increased carbon dioxide emissions and the absence of vegetation cover. Consequently, Iraq is confronted with substantial obstacles in its efforts to mitigate the consequences of climate change (Jaff, 2023).

The quantity and intensity of storms in urban areas will increase due to climate change, which will have a significant impact on water resource systems. This can elevate the likelihood of flash floods, necessitating the enhancement of current non-resilient stormwater drainage systems or the development of new systems that are suitable for long-term use. To address these obstacles, it is imperative to maintain vigilant updates to wastewater drainage systems and design standards (Laouacheria et al., 2019).

1.2 The importance of stormwater management in urban areas

Rainwater is a natural and efficient method of replenishing groundwater. The effective administration of rainwater is essential for the preservation of water resources and their utilization in irrigation and other agricultural applications. Inadequate management results in the accumulation of undesirable water and floods, which inflict damage on infrastructure. Floods, particularly rapid flash flood events that are the result of heavy rainfall, are the primary cause of weather-related disruption in the transportation sector and are anticipated to persist in the future. This issue is particularly exacerbated on the urban road network as a result of the high ratio of impermeable surfaces that obstruct water infiltration to the soil layers. Debris and silt are more likely to clog sewers during periods of heavy rainfall, which can result in overland flows that overflow. Roadside ditches

are critical elements of urban drainage systems and road structures. It is a critical component of the stormwater drainage system, as it is responsible for collecting and transporting rainwater discharge to estuaries or natural rivers and enhancing water quality through increased infiltration. Therefore, a roadside drainage system that is properly engineered and designed It has the potential to reduce pollutants and runoff using scale dilution and runoff filtration.

Numerous investigations have incorporated rainfall-runoff simulations to improve the operation of rainwater networks (Mohsen et al., 2020). (Mohsen et al., 2020).The U.S. Environmental Protection Agency (USEPA) devised the stormwater management model (SWMM), which has been implemented in a diverse array of catchment areas worldwide (Bhaduri et al., 2001, Selvalingam et al., 1987).have developed EPA-SWMM, a dynamic simulation model for rainfall runoff, Which simulates the quality and quantity of surface runoff for a specific event or group of events or a continuous and long-term simulation.(Ahmed et al., 2017). The SWMM is a widely employed instrument for the planning and design of urban stormwater sewer systems (Gironás et al., 2010).

1.3 The role of drainage system simulation in rainwater networks

Drainage system simulation allows the analysis and design of rainwater networks and the correct sizing of infrastructure, ensuring that the risks associated with flooding are reduced. It also allows for the presentation of a scenario to improve sustainability and the development of an emergency plan in the event of an increase in the amount of rain discharged to the network, which increases the network's ability to withstand any future challenges. Examples of this software are the SWMM (Storm Water

Management Model) program for modeling rainwater network hydraulics and analyzing system performance under different scenarios.

1.4 Environmentally friendly infrastructure

Infrastructure is a combination of environmental, social, and economic objectives and benefits that require adaptation for the development, evaluation, and implementation of the Low-impact development LID (Chini et al., 2017).With the increase in impermeable lands and increasing urbanization, stormwater runoff management becomes increasingly challenging, which is one aspect of urban sustainability. Planners and engineers are compelled to contribute to mitigating floods and enhancing the quality of the water they receive in response to heightened political, social, and environmental demands (Chini et al., 2017)Low-impact development (LID).

Developers have concentrated on rapidly expanding urban areas, seeking the most effective management practices to mitigate flood risks. Acknowledging that LID is among the most efficient solutions for managing urban runoff, the hydrological simulation function for Low-impact development (LID) structures was incorporated into the USEPA's SWMM5.2 framework in 2009.

1.5 Problem state

The world faces comprehensive and economic challenges related to rainwater drainage systems, which require developing special solutions in urban areas. Modeling and simulation are modern methods for building the rainwater network.

Due to the addition of sewage quantity by the residents, urbanization, and climate change during the rainy season, the runoff drainage system in the study location is subject to inundation. Due to climate change, the region is witnessing an increase in the amount and intensity of rainfall that exceeds the design intensity of the network. The system's drainage capacity was ultimately exceeded by this increase, leading to an inundation.

The urban inundation during the rainy season results from land use and climate change. The quantitative estimation of rainfall can assist in the administration of urban drainage systems in the context of climate change by assessing the impact of rainfall patterns on runoff.

1.6 Thesis Objective

The primary objective of this study is to offer technical assistance to decision-makers in the Karbala region regarding the efficacy of rainwater drainage networks in the context of climate and population change. The primary objectives of this study are as follows:

1. Use the SWMM model to develop a stormwater management system performance simulation model to simulate significant rainfall events in the studied area.
2. Evaluate the developing stormwater system performance efficacy after implementing a solution using SWMM to reduce flood effects.
3. To create a solution by utilizing simulation in the SWMM program:

a. employing the most effective administration principles, including Low Impact Development (LID).

b. To propose an alternative solution, adding three conduits to the main pipeline network would reduce the volume and number of manholes that flood.

The findings will be employed to assist decision-makers in confronting floods and to develop future solutions.

1.7 Scope of the study

The scope of the study is as follows:

a) The study was conducted in Karbala, Iraq. It is located about 100 km southwest of Baghdad's capital, specifically in the Al-Wafa neighborhood.

b) The maximum rainfall in the study area was considered when it coincided. The study uses historical data from the system to analyze the maximum daily precipitation over a 20-year period for the Karbala Weather Station.

c) Land use maps are drawn in the study area to identify residential areas, parks, and roads. Contour, slope, and land use maps are drawn using ArcGIS software (ArcMap10.8). This was done using information received from the Karbala Municipality Directorate to demarcate commercial, industrial, and public places. This program also displays the storm system hydraulic data map, the terrain map, and the digital image of the study area file. Future rainfall events were then modeled using Stormwater Management Model (SWMM5.2) software from the observed streamflow data to obtain the best simulation results.

d) The rainwater network for the study area was analyzed using the Stormwater Management Model (SWMM v5.2). Its performance was

evaluated in the current and future periods based on the percentage deficit in the city's rainwater network to determine the extent of its impact.

1.8 Thesis Methodology

The current investigation's methodology

The work steps in this investigation can be summarized as follows:

1. Hydrological data refers to historical data on daily precipitation for 40 years (1984-2024), which is obtained from satellite data sourced from the Global Energy Resources Forecasting Project (POWER) from the National Aeronautics and Space Administration (NASA) research.
2. The relationship between rain intensity and frequency duration curve (IDF) for Karbala was derived for various periods using the collected daily rainfall data. Then, trace these curves.
3. Gather land use data, topographic data, soil characteristics data, digital images of the study area, and hydraulic data from the Karbala Sewerage Directorate [DSK]. This encompasses data on rainwater networks, the study area's features, the area, manholes, pipelines, and all specific accessories. The data acquired from the Directorate was used to construct a network of points and lines using GIS. This network was subsequently prepared for export to SWMM using ancillary software (SSA and GIS).
4. Subsequently, the Stormwater Management Model (SWMM v5.2) calibrates and verifies the collected data to achieve the most accurate flood assessment and simulation results.
5. Utilize the previously obtained data to analyze the rainwater network in the SWMM program, and the storm network in the study area was evaluated using the SWMM model after the expected rainfall intensity was applied to the storm network using the model. This was achieved by applying expected

future rainfall events, estimating the flood rate, and proposing solutions to mitigate and treat floods in the study area. To successfully mitigate future flooding, it is essential to ascertain the proportion of the deficiency in the city's stormwater network and to formulate appropriate design scenarios and strategies.

1.9 Thesis Structure

The Thesis is divided into two components. The initial step is a literature evaluation that examines the various methods and processes required to assess and upgrade a stormwater system. The second section was dedicated to the essential tools regarded as the primary focus to facilitate our work: the EPA SWMM program, the SSA program, and the Geographic Information Systems (GIS) program.

1. The initial chapter delineates the significance of the study, the background of the study, the objectives of the study, the problem statement, the thesis's structure, methodology, and scope.
2. The second chapter explains the literature and studies on administering floods in urban areas. It pertains to the flood simulation model (SWMM) in urban areas and discusses the correlation between urbanization, flooding, and fluctuations in rainfall intensity.
3. The third chapter delineates the methods employed in the study and provides a comprehensive discussion of the methodology employed in collecting, analyzing, and simulating data using the SWMM model. This chapter covers the study area's hydrological, hydraulic, and field data, the methods used to construct the model, time series, intensity, duration, and frequency (IDF) curve.

4. The SWMM model was employed to analyze the rain intensity model in the study area, and the results are presented in the fourth chapter. The flood model results are reviewed, and a future proposal is proposed to enhance the quality of sanitation and reduce and mitigate rainwater network overflows during rainfall seasons.

5. Chapter Five (Conclusions and Recommendations) presents the research's conclusions, recommendations for improvement, treatment, adaptation to challenges, and future study recommendations.

1.10 Limitations

1. The determinants in the program were used based on the soil characteristics in Karbala.

2. The rainfall intensity used in the study for the return periods of 2, 5, 10, and 20 years was 40.5 mm/hr, 60.4 mm/hr, 73.6 mm/hr, and 86.3 mm/hr, respectively.

3. The percentage of the unimplemented and implemented area was estimated directly from the aerial photograph and the land use map appendix from the urban planning. The unimplemented percentage ranges from [25% to 95%] (Panos et al., 2018).

4. Land use maps in the study area from Karbala Sewerage Directorate for the year 2022.

5.The total area is about 0.701 square kilometers. The previous area, which includes green spaces and unpaved areas, constitutes about 30%. The unimplemented area, which represents roofs, paved areas, and sidewalks, constitutes about 70% of the total area. There are 237 sub-basins within the rainwater drainage network used in the case study.

6. Draining rainwater during rainy weather and with a design rainfall intensity of 12 mm/hr.

Chapter Two: Theory Concept of Literature Review

2.1 Floodwater and Surface Runoff

Stormwater falls on the ground after rain, seeps from a certain location, and carries debris, organic matter, fertilizers, and oil residues. It has the potential to contaminate water heading to a river. Only rainwater falling directly on the ground surface is considered pure stormwater. Despite this, stormwater is very useful if reused properly and achieves savings.(Hatt et al., 2004) Mitigate downstream environmental consequences and supply potable water. Stormwater is produced in urban areas due to the discharge of rainwater from impervious or hard surfaces, such as roofs, roadways, driveways, and footpaths. Chemical pollutants, nutrients, sediments, and debris can be carried into waterways and erosion due to poor stormwater management, which can cause issues both on and off-site. Additionally, inundation and erosion may result from an elevated level of discharge. (Seneviratne et al.). In applications that do not require high-quality water, such as garden irrigation, stormwater that is appropriately managed has the potential to replace imported water (Hatt et al., 2004). These measures are instrumental in safeguarding the environment, property, and infrastructure from harm (Eckart et al., 2017). Stormwater management also safeguards water quality.

Typically, floods occur over days when the rivers cannot accommodate the excess rainfall, resulting in the water extending over the adjacent land (the floodplain). However, this can rapidly occur in the event of a substantial quantity of heavy rainfall within a short period. Compared to other forms of flooding, these flash floods occur without warning and cause the highest number of human fatalities (Adeyi et al., 2020).

Low-impact development and green infrastructure are stormwater management strategies that can mitigate the quantity of pollutants that penetrate our waterways (Liu et al., 2015). These methods enhance on-site water balance, increase groundwater recharge, and utilize rainwater, all while decreasing downstream inundation (Chen et al., 2016). To reduce the risks associated with flooding in urban areas, it is imperative to have a drainage system that is well-designed and capable of effectively collecting and managing precipitation. Urban regions are progressively encountering difficulties in drainage systems as a result of fast urbanization and climate change. These issues may lead to floods, significant infrastructure damage, interruption of social and economic services, and increased human vulnerability (Afrin et al., 2021, Bibi et al., 2023).In recent decades, the proliferation of impermeable surfaces such as highways and buildings has drastically transformed urban environments, diminishing vegetation and aquatic ecosystems. To mitigate these challenges and improve urban resilience, the implementation of green infrastructure provides a sustainable solution to reduce the strain on drainage systems resulting from these alterations (Fletcher et al., 2015, Xu et al., 2023).

2.2 Management of Urban Discharge

There was a confluence of sewage and precipitation discharged into the recipient water bodies before World War II. The environment and downstream residents are adversely affected by the combined drainage system.

distinct drainage channels have been implemented to optimize the conveyance of wastewater and precipitation. Rivers, lakes, and other bodies of water are directly filled with urban precipitation. , while municipal

effluent is processed at a sewage treatment facility (Kim and Li, 2016). The local flood issue can be mitigated by employing a diverting drainage system to effectively discharge rainfall into the water bodies at a specific time. The United States implemented the "Clean Water Act" in 1973, comprising regulations addressing precipitation retention (USEPA, 1999). The regulations have mandated the implementation of extensive rainwater depressions in certain regions to regulate the amount of rainfall. The detention function enables them to effectively and directly resist flood peaks.However, they do not have any discernible impact on reducing flood peaks in the downstream region. In the aftermath of the 20th century, a novel sustainable urban rainfall management concept was introduced, motivated by sustainable development. The Global Water Partnership (GWP) has encapsulated the integrated management of discharge resources to address water, land, and related challenges. Subsequently, the sustainable development of ecosystems is not jeopardized by the coordinated development and management of resources, as they accomplish a balanced optimization of economic and social benefits (Stålnacke and Gooch, 2010). Water Sensitive Urban Design (WSUD), Sustainable Urban Drainage Systems (SUDS), Low Impact Development practices (LIDs), Green Infrastructures (GI), and Best Management Practices (BMPs) are among the technologies that are included in sustainable rainwater management. These technologies have been developed by researchers from various countries (Charlesworth et al., 2003). Through the scientific and meticulous design, construction, operation, and management of urban wastewater systems, the primary objective is to mitigate the emissions of non-point source pollutants and the increase in urban discharge. Indeed, these technologies and concepts are articulated in a multitude of ways (Wang et al., 2003). The most

representative and widely used among these innovative urban stormwater management concepts in urban construction are BMPs and the later proposed LIDs. Peak control, discharge volume control, and pollutant control are implemented as best management practices (BMPs) for precipitation management through the end-control method. Source control is the primary objective of LIDs, designed to enhance water quality and regulate discharge.

2.3 Flooding: Causes and Consequences

The flooding is a condition in which wastewater and surface water either remain on the surface or penetrate buildings due to their escaping from or being unable to enter a drain or sewer system. Heavy rainfall is frequently associated with flooding; however, floods can occur in various ways that are not explicitly linked to ongoing weather events. Consequently, a comprehensive account of inundation must encompass processes that may have minimal or no correlation with meteorological events.

Typically, inundation is the result of both hydrologic and meteorological processes. The specific characteristics of a deluge are determined by the behavior of the precipitation and the circumstances in which it is likely to occur, including the quantity of antecedent rainfall and the condition of the soil. It is exceedingly improbable that it will be feasible to render precise predictions regarding flooding events; however, it is unquestionably feasible to forecast the probability of most floods.

Sewage spills are frequent in cities, and floods disrupt the normal drainage systems, posing a significant health hazard. Additionally, standing water and wet materials in the residence are a concern. Long after a flood, bacteria and viruses damage materials, provoke allergic reactions, and cause disease.

Floods have the potential to disperse substantial quantities of water and suspended sediment over extensive areas, thereby replenishing agricultural lands with valuable soil nutrients. Conversely, the destruction of agricultural land, buildings, and crops can result from soil erosion substantial quantities of rapidly flowing water.

2.4 Urbanization's influence on the natural hydrological cycle

The natural hydrological cycle is characterized by the transfer of water from the atmosphere to the Earth's surface through rainfall, its subsequent entrance into the ocean through discharge, and its return to the atmosphere. Interception, precipitation, discharge, infiltration, and evaporation comprise the process. The initial intercept of precipitation by vegetation occurs as it descends to the surface. Rainwater is not only retained in the underlying surface, but it also penetrates the ground. Ultimately, some precipitation is released into rivers, which then flow into the oceanic system. A portion of the precipitation Ultimately, the flora undergoes evaporation, discharging its stored energy into the atmosphere. The precipitation collected in the depression evaporates into the sky or permeates the soil. If water has been infiltrated, it will either be deposited in the subterranean water layer or used by the plants upon its return to the surface soil (Chin et al., 2000). The natural hydrological cycle has been significantly influenced by the gradual concentration of human beings in cities, the construction of production and living facilities, and the complete alteration of the morphological characteristics, resulting in the establishment of an urbanization system that is distinct from the natural state (Dion, 2002).To meet the needs of urban life, urbanization, and urban expansion transform natural land into a development area. Urbanization results in the hardening of the underlying

surface, with impervious surfaces replacing the original vegetation and soil. As a result, the quantity of water absorbed by the surface and the amount intercepted by vegetation decrease. Production and confluence parameters, such as surface discharge and confluence time, have been modified due to water impermeability, stagnant water bodies, drainage systems, and river channels. In addition, stormwater discharge will also include pollution that results from atmospheric deposition (Islam, 2023). The hydrological cycle's transformations before and after urbanization are illustrated in (Figure 2.1).

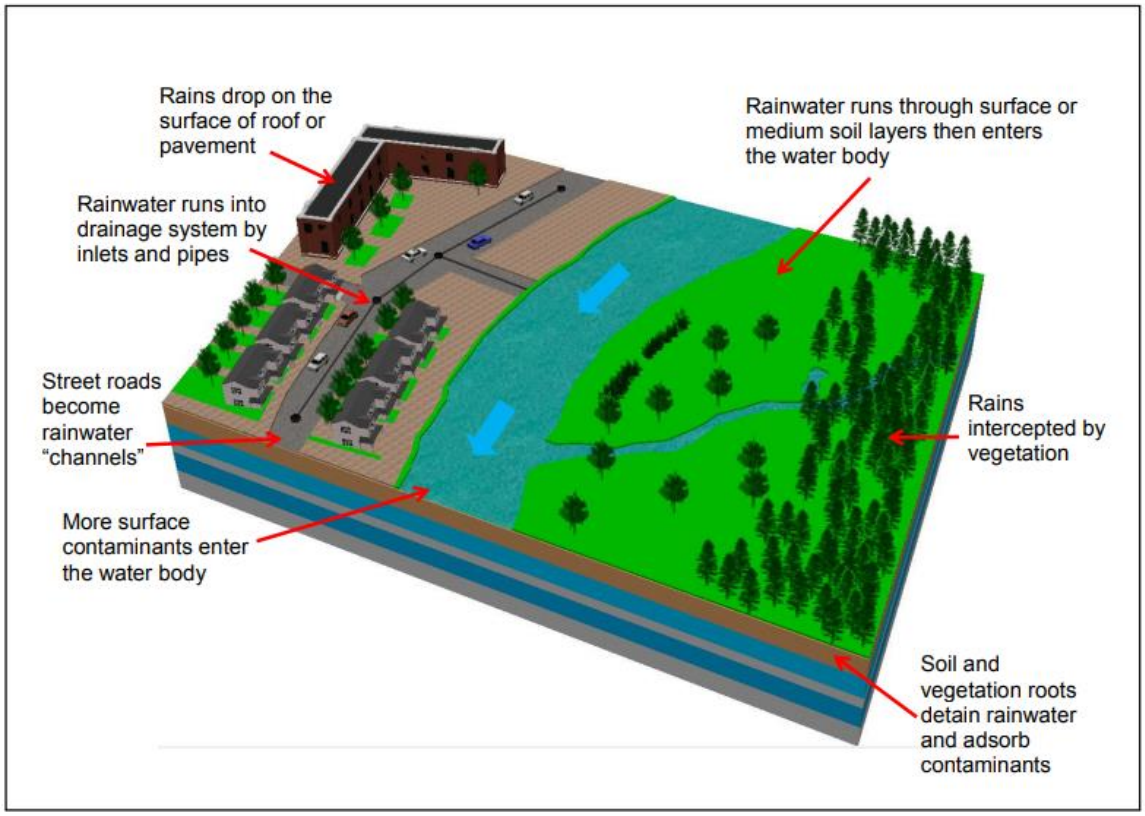


Figure 2-1 shows the effect of urbanization on the natural hydrological cycle (Chen, 2019).

The proportion of pervious and surface has consistently decreased, which has disrupted the region's natural hydrological cycle and is the

primary indicator of urban expansion. This has the following primary effects on the hydrological status of the area:

2.4.1 The effect of urbanization on discharge

level Urbanization induces surface discharge, as rainfall previously absorbed by the land now falls on impervious surfaces. Before a watershed is established, most rainfall can accumulate, infiltrate, and be evapo-transpired by previous fallow land. Roads, footpaths, parking lots, driveways, and rooftops are among the impervious surfaces that obstruct the passage of rainwater over a substantial fraction of this previous land after development. Additionally, a substantial portion of this impervious area is directly connected to a drainage system, preventing rainwater from infiltrating by traversing the previous ground. This area is known as the Directly Connected Impervious Area (DCIA). Efficient and rapid transportation of runoff to the recipient stream or water body is the primary objective of the typical storm drainage system. These factors lead to a higher total volume, resulting from more frequent and larger peak volumes. In addition, the drainage system directly connects a substantial portion of the impervious area, resulting in substantially eradicating biological processes. Thus, pollutants are transported swiftly and untreated to the receiving water bodies. (Islam, 2023). The natural hydrological cycle is disrupted in numerous ways concurrently with urban sprawl. As a result of the compaction and hardening of the soil, the amount of percolation has decreased, discharge has increased, and the amount of savings in the depression has decreased. The reason for this is the consequent rise in impervious areas. A decrease in transpiration results from a decrease in trees and vegetation. Due to the decrease in effective rainfall storage systems and

the increase in impervious areas, the time required for runoff is reduced. The quantity of infiltration and the increase in impervious areas have resulted in a decrease in groundwater recharge. During the dry season, the flow of rivers and lakes decreases due to the absence of basal flow. The expansion of downstream channels results from the rise in runoff (!!! INVALID CITATION !!! (Federation and . 1998, Prevention, 2005, Arnold Jr and Gibbons, 1996)). According to (Arnold Jr and Gibbons, 1996), approximately 30% of precipitation is returned to the atmosphere evaporation in a densely developed region with over 75% impermeable surfaces. Infiltration into the ground accounts for 10% of precipitation, while 5% is absorbed into the earth. The remaining 55% is directly formed as runoff. Furthermore, typically, the runoff coefficient, which is the ratio of runoff to rainfall, is directly proportional to the degree of imperviousness, as determined by the US Environmental Protection Agency (USEPA) (Division, 1982). According to the research conducted by (Fitzpatrick et al., 2005), in urbanized areas, the greatest discharge is three times greater than that in undeveloped areas, the peak duration is reduced by one-third, and the storm runoff volume is two to four times greater than that in undeveloped areas before urbanization. The most significant change in a particular location before and following urbanization is depicted in Figure (2-2). Consequently, urbanization substantially extended the time until the flood

peak occurred.

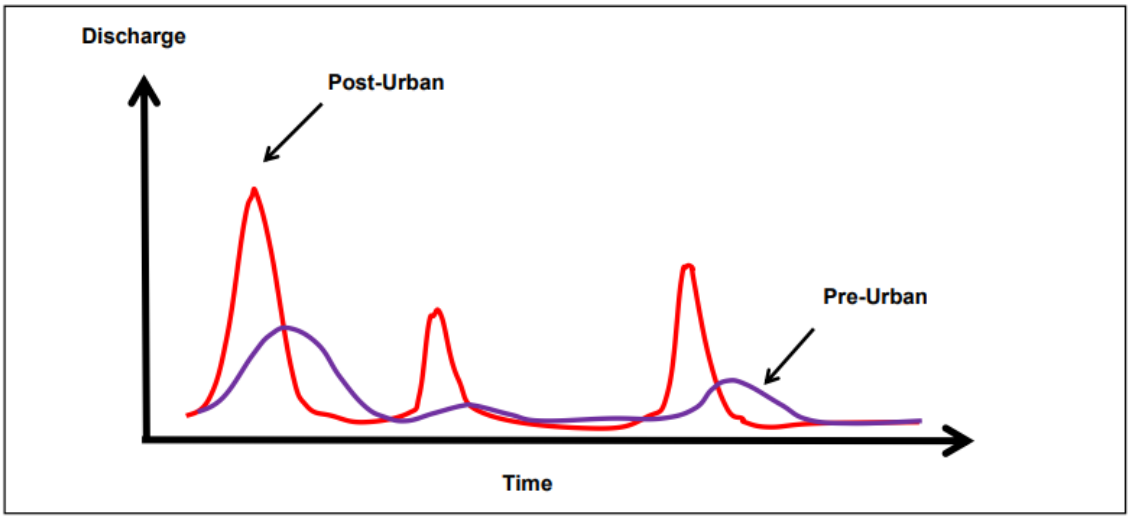


Figure 2-2 Surface runoff is subject to change before and after population development.(Movahedinia et al., 2019).

2.4.2 Urbanization's influence on water quality

Human activities produce many types of pollutants as a result of urban expansion, and its diversity has become more complex. Consequently, the deterioration of water bodies is a result of the pollutants they receive through flowing water, such as decomposition and erosion. The impervious area in urban areas is increased by urbanization, which also leads to an increase in sand production and soil erosion(Prevention, 2005). Sediments, bacteria, nutrients, toxic compounds, and other pollutants comprise the majority of urban runoff (Adams, 2000, Division, 1982). From 1978 to 1983, the National Urban Runoff Program in the United States monitored harmful emissions from 28 cities. The urban discharge in these cities was distinguished by high bacterial concentrations, high sediment production, and high heavy metal concentrations (Vorreiter and Hickey, 1994, Field, 2018). (Zimmer et al., 2007)According to the report, runoff-carrying

pollutants were responsible for the contamination of 1/3 to 1/2 of rivers. The third or fourth main source of river contamination is evaluated as municipal discharge or precipitation in the biennial national water quality inventory report of the United States Environmental Protection Agency (USEPA).

Rivers (USEPA, 2007; USEPA, 2009; USEPA, 2005). (Yu-Jie and Xin, 2022) Utilized Remote Sensing and GIS to examine the hydrological effects of urbanization on runoff in the Yangtze River Delta, China. The watershed's water filtration capacity in the river basin has declined, resulting in poor river water quality owing to increased urbanization. Recently, international research has focused its studies on the effects of urban expansion and its impact on water quality, with a primary focus on the accumulation of nutrients and the nutrition of nitrogen and phosphorus(Varis and Somlyódy, 1997, Eshelman, 1991), as well as the impact of heavy metals on aquatic ecosystems.(Chang et al., 2004, Pouyat et al., 2007, Bannerman et al., 1993), Increased sediment volume (Nelson and Booth, 2002).

2.4.3 Environmental impact on water bodies as a result of urban expansion

The direct consequence of increased water impermeability in urbanization is a decrease in groundwater recharge and an increase in surface discharge. The primary factors contributing to ecological injury in downstream receiving water bodies are fluctuations in surface runoff volume, peak, and duration (Fitzpatrick et al., 2005, Walton et al., 2007, Nelson and Palmer, 2007) .Additionally, the conversion of the surface with natural vegetation sowing to impervious surface is a consequence of the increase in impervious area. Vegetation coverage, pollutant removal, and the interception effect are

all diminished by this transformation. The ecological equilibrium of the receiving water bodies is disrupted and the ecosystem is negatively impacted by the accumulation of a substantial quantity of sediments and pollutants (Carle et al., 2005, Greer and Stow, 2003).

2.5 Transportation of stormwater discharge

In cities, the replacement of natural green infiltration surfaces (i.e., natural soil cover) with impervious surfaces (such as concrete roadways, rooftops, and buildings) has a substantial impact on urban stormwater runoff and generation (EPA, 2003). As a result, stormwater is transported downstream significantly faster, as water travels more rapidly over hard surfaces than natural surfaces. The outcome will be a faster-moving runoff flow (with a higher peak flow) that penetrates the urban drainage system faster in urban areas. However, the urban runoff flow will also dissipate significantly faster than natural green areas, resulting in a higher peak flow (Beiro and Manso, 2012).The discharge volume before and after urbanization of natural surfaces is depicted in Figure (2-3).

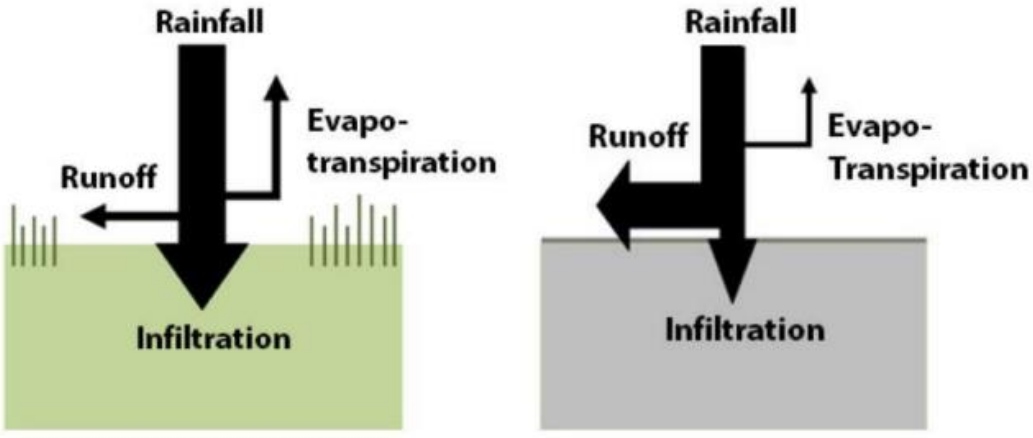


Figure 2-3 Water transportation before and after urbanization (Islam, 2023)

2.6 System for Draining Stormwater

2.6.1 Flood drainage system jobs

The drainage system is designed to capture groundwater and surface water during floods and rainfall and direct it away from the area. Therefore, the drainage system must be protected from erosion because the main goal of the drainage system is to protect the environment, public health and sustainable development.

To safeguard potable water sources from contamination by waterborne waste, prevent the spread of disease through contact with fecal and other waterborne waste, and transport runoff and surface water away while minimizing public hazards, drain and sewer systems are implemented. Furthermore, the impact of drain and sewer systems on the receiving waters must satisfy the relevant authority's requirements or any national or local regulations (Hydrology, 2007).

2.7 Different types of floodwater drainage systems

The primary function of road drainage structures is to prevent water from accumulating on the roadway surface by acting as conveyance structures. Water is removed from the road surface, and overland discharge is prevented from infiltrating the carriageway through effective drainage structures. A drainage system is composed of all the essential components required to drain the substructure accurately. These components may include stormwater drainage pipelines, channels, and culverts, as well as open and closed ditches with pipe drains (Hydrology, 2007).To prevent precipitation accumulation on streets for protracted periods, it is necessary to ensure that

discharge from streets is directed into drainage channels, watercourses, and pipe systems at low points and intervals. According to the Storm Water Design Criteria Manual for Municipal Services (May 2011), stormwater volumes on any street are limited to a maximum depth of 0.3 m and a maximum flow velocity of 2 m/s. Streets could be planned to temporarily transport flow as part of the primary drainage system during storms that surpass the design storm of the minor drainage system (i.e., a storm event with a return period exceeding five years).

The Manning Equation will be employed to ascertain the flow conveyance capacity of the street, with a Manning's resistance coefficient of 0.013 for bitumen surfaces and 0.015 for concrete surfaces. The designer must maintain a traveled way of sufficient width on all roads to ensure the secure passage of all vehicles in both directions for storms up to and including the 5-year-return-period storm. The designer must guarantee that the depth and spread of flow do not exceed the curb height and the right-of-way width during storms up to and including the major design storm (1.2 times the 100-year-return-period storm) for residential streets and local collector streets (Storm Water Design Criteria Manual for Municipal Services, May 2011). The primary components of an urban drainage system are as follows:

➢ Property drainage

➢ Street drainage (consisting of both piped and surface flows)

➢ Trunk drainage (consisting of vast conduits, typically open channels, located on lands designated for drainage purposes)

➢ Receiving water bodies

2.8 Low Impact Development (LID)

LID includes a set of sustainable practices and technologies . It is a type of green and innovative infrastructure for managing rainwater and aims to reduce its negative effects. Green infrastructure ensures the provision of green spaces such as parks, green roofs, and urban gardens for all residents regardless of their social and economic status, which enhances social justice in the use of these natural spaces. Green infrastructure contributes to improving public health by reducing pollution, reducing health disparities, improving air quality and reducing diseases associated with high temperatures, especially in marginalized communities. Green infrastructure projects support economic development and reduce social and economic disparities by providing job opportunities, especially in areas that previously suffered from a lack of services, which contributes to stimulating the local economy. Improved green spaces can also contribute to reducing crime and violence rates within communities, provided that they are well designed and maintained to achieve these benefits.

Environmental Consequences Green infrastructure enhances rainwater infiltration into the soil and reduces pollutant runoff, improving air and water quality by reducing impermeable surfaces. In addition, it contributes to ecological balance and increases biodiversity by providing natural habitats for wildlife and mitigating the effects of urbanization on the natural hydrological cycle (Guan et al., 2015, Kong et al., 2017, Line et al., 2012).The primary goal of LID is to reduce stormwater runoff, enhance urban sustainability, and improve water quality. In the early 1990s, the Prince George's County Department of Environmental Resources began developing the concept of LID However, the term first appeared in a study by Barlow et al. in 1977 to reduce runoff management costs (Barlow et al.,

1977). (Eckart et al., 2017) The primary goal of LID is to regulate the quantity and quality of stormwater, manage runoff near its source, enhance natural hydrological processes, and provide environmental benefits. LID techniques include a range of approaches, such as:

- Barrels or tanks for all rainwater
- Purification cells or biological gardens
- Green roofs
- Rain gardens
- Permeable pavements
- Vegetation channels
- Trenches and infiltration basins
- Roof gutter separation
- Tree box filters

These methods aim to manage stormwater drainage sustainably and in an environmentally friendly way by enhancing ground infiltration, evaporation, transpiration, and removal of pollutants. The study will focus on rain gardens for the additional benefits they provide in managing stormwater drainage..

The following discussion will address the principles, design, and benefits of these two methods.

These practices of LID are strategic for urban flood control that encourage stormwater infiltration and retention. For example, permeable pavements and cells are effective solutions for recovering large amounts of surface runoff. Permeable cells are designed to capture surface runoff in impermeable areas such as parking lots, roofs, or streets, where the water is directed to percolate through layers of soil and vegetation. Plants within the

cell, including grasses, shrubs, and trees, absorb and decompose nutrients and pollutants, contributing to water purification (Sirova, 2015).

2.9 Sustainable Urban Stormwater Management: The Role of Low Impact Development (LID) and Bioretention Systems :

Through the incorporation of climate change considerations, stakeholders develop a more profound comprehension of sustainable urban development. Utilizing a nature-based methodology, LID alternatives offer a sustainable and comprehensive approach to the reduction of pollutants, peak flow rates, and discharge volumes. The incorporation of Low Impact Development (LID) as a retrofitting measure in urban stormwater infrastructure can significantly enhance adaptation to climate change and alleviate associated stresses (Eckart et al., 2017, Ahiablame et al., 2013). The efficacy of Low Impact Development (LID) in mitigating flood hazards within urban environments has been assessed through numerous studies employing a wide range of parameters. In 2016, Ahiablame and Shakya revealed that the three LID practices were implemented at varying levels, resulting in a discharge reduction in the study catchment spanning from 3% to 47%. (Ahiablame et al., 2013, Zahmatkesh et al., 2015) discovered that employing LID controls resulted in a 41% decrease in effluent volume (Zahmatkesh et al., 2015). The Bioretention System BC is one of the most frequently implemented LID techniques. Stormwater runoff originating from impervious surfaces, such as roadways, parking lots, and rooftops, can be effectively collected and treated through the implementation of a bioretention cell. A stormwater discharge from impervious surfaces that is effectively managed by a landscape depression that is intentionally designed. Typically, it consists of several layers, including a media layer comprised of sediment, soil, and organic

matter, which serves to regulate drainage, a surface foliage layer, a storage pool with a depth of 15 to 30 centimeters, and a variety of vegetation. The fundamental objective of bioretention systems is to replicate the natural hydrologic cycle by retaining and purifying effluent, thereby reducing flow rates and volumes. The primary function of bioretention systems is to prevent soil erosion, recharge groundwater, enhance the aesthetic appeal of the surrounding neighborhood, and provide habitat for Excess water is discharged through underdrain conduits, while incoming effluent is infiltrated through the media layers in the bioretention cell. Additionally, water loss can be accomplished through exfiltration and evapotranspiration. Water is lost from the drainage system through exfiltration, which occurs when it is assimilated into the existing soil or percolates. Vegetation impacts the assimilation of nutrients and water from the media in the bioretention cell. If the media becomes inundated, overflow may occur, causing transient ponding until the water level reaches a predetermined control elevation, at which point it begins to discharge. wildlife, and improve the base flows in local streams. Additionally, they provide a variety of benefits. (Shafique and Kim, 2015, Sirova, 2015).(Davis et al., 2009, Eckart et al., 2017, Garcia-Cuerva et al., 2018, Liu and Fassman-Beck, 2017).

The media layer is an essential element in the primary filtration process, as rainwater passes through the various levels of the biological retention system and undergoes a sequential filtration process. This process contributes to the effective removal of debris, particles, sediments, and pollutants from the surface runoff, ensuring that the water is purified before being discharged into the stormwater conveyance or receiving systems. The system reduces the speed of surface runoff, as the surface vegetation layers help trap sediments. These systems take advantage of the chemical, biological, and

physical properties of plants, microbes, and soil through different unit processes within the biological retention cell to effectively remove pollutants from urban waste. Studies have shown the ability of these systems to reduce peak flows, runoff volumes and pollutant loads, as well as enhance evaporation by increasing the delay time and enhancing plant uptake. Figure (2-4) shows a practical application of these systems through a field-scale biological retention cell(Fassman-Beck and Saleh, 2021, Lisenbee et al., 2022, Liu et al., 2014).

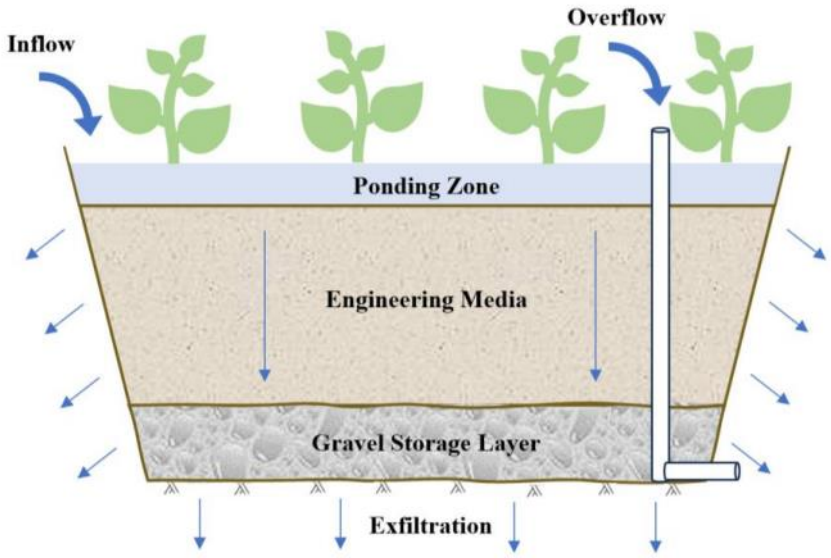


Figure 2-4 Bioretention facility and its hydraulic pattern (Fassman-Beck and Saleh, 2021, Liu et al., 2014).

2.10 Permeable Pavement: A Sustainable Solution for Urban Runoff Management

Polypropylene (PP) is a type of permeable pavement that effectively contributes to reducing the negative impacts of roads and parking lots on municipal water systems thanks to its porous surface and open gradation. This type of pavement allows rainwater to seep through its surface, reducing the negative consequences of water drainage in urban environments (Brattebo and Booth, 2003) and is a practical solution to reduce the effects of urbanization on hydrological processes. Studies have shown that permeable pavement reduces runoff volumes, improves infiltration rates, and reduces the risk of water pollution and flooding.(Andersen et al., 1999) The hydrological performance of permeable pavement in the UK was investigated, and results confirmed that particle size distribution and water retention in surface aggregates and bedding materials significantly affect the mechanisms of evaporation, drainage, and water retention during the rainfall interval. As a result, the concentration period during storms is delayed, which significantly reduces peak flows. The PP system captures and treats stormwater due to its high infiltration rates, which helps in drainage while providing a durable and visually attractive surface. Research indicates that permeable pavement is a strategy for sustainable urban development, as it contributes to improving runoff management and reducing the impact of urban (Andersen et al., 1999).The primary objective of these pavements is to enhance the infiltration of stormwater through the surface and bedding

layers, which improves the overall hydrological performance of the urban environment.

These systems comprise concrete slabs or pavers with open joints allowing water to infiltrate. The pavement layer can absorb the rain that descends on the surface or be trapped on the surface. A stone reservoir is the destination for the remaining water, which either infiltrates downward or flows as surface discharge. The stone reservoir temporarily stores excess water during heavy rainfall, while the high permeability of the pavement strata reduces surface runoff. The underlying subsoil ultimately absorbs the stored water Figure (2-5)Permeable paving is an environmentally effective solution for stormwater management, as it enhances soil penetration, reduces runoff, and contributes to reducing the risk of urban flooding.

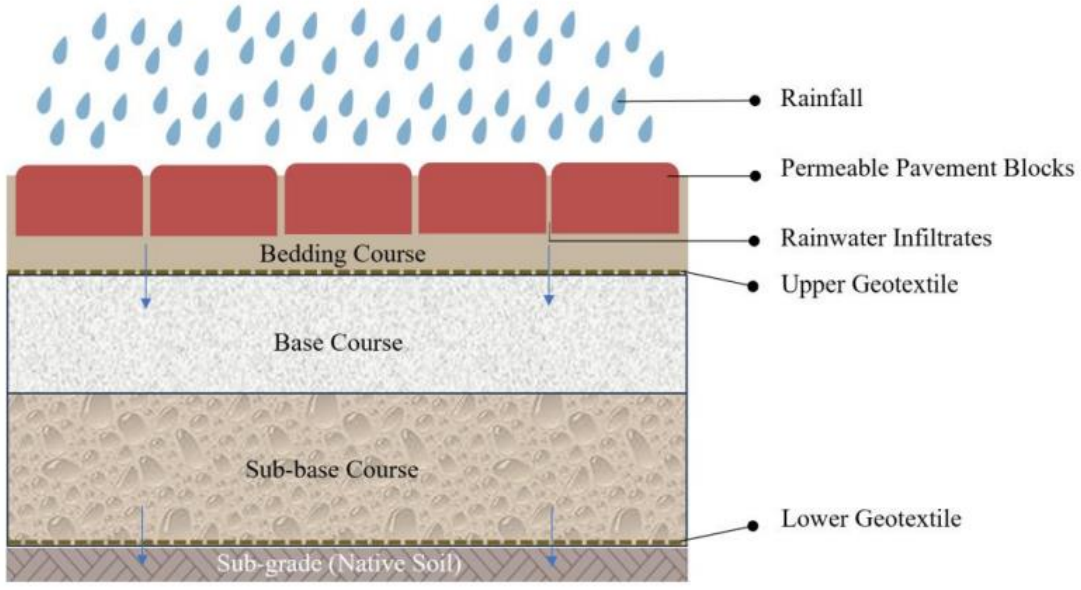


Figure 2-5 Representative permeable pavement schematic diagram (Shafique et al., 2018)

This thesis evaluates the effectiveness of LID techniques in reducing urban flooding by employing SWMM in two-dimensional simulations under varying return periods and LID implementations.

2.11 Low-impact development practices (LIDs)

The Environmental Resources Agency of Prince George County, Maryland, introduced a novel concept of runoff management known as low-impact development (LID) . The LID primary objective is to enhance the utilization of decentralized, small-scale rainwater treatment facilities or practices (LID) that are founded on micro-scale landscape control. This approach ensures that the hydrological characteristics of the region remain essentially unchanged from prior to development. Additionally, this method mitigates the ecological consequences of regional development and establishes a site with optimal hydrological functionality. (Askarizadeh et al., 2015). Currently, Figure (2-6) provides a summary of typical LID.

Vegetation is cultivated in an engineered soil mixture in a depression known as a **rain garden** or bioretention, which is located above a gravel drainage bed. Both direct rainfall and discharge captured from the surcharge can be stored, infiltrated, and evaporated.

Another embodiment of the bioretention cell is the **green roof**, which is distinguished by the presence of a soil layer.A unique drainage mat material is placed on top of the roof to remove surplus percolated rainfall.

Infiltration a trench is a narrow channel filled with sediment intercepting drainage from upslope, extending the time for captured discharge to permeate native soil and enhancing storage capacity.

The **Vegetative swale** is a channel or depressed area covered on the slope sides with other vegetation and lawns. It slows down the conveyance of collected effluent into the native soil beneath it, facilitating its infiltration.

During storm events, a **Rain barrel** (or cistern) is a container that captures roof runoff., and can either discharge or re-use the rainwater during dry periods.

Permeable pavement is an excavated area filled with gravel and paved with porous material. Concrete, asphalt, or paver blocks are utilized to facilitate the infiltration of rainfall into the native soil of the site at a natural rate.

Figure 2-6 Types of LID (Lee et al., 2018)

2.12 Modeling-based Assessment of LID

With the development of pollution control systems, the evaluation of their effectiveness in developed countries is no longer limited to taking samples and direct monitoring. Simulation models of rainwater flow and pollution control systems have been developed, which has contributed to achieving remarkable progress. For instance, (Villarreal et al., 2004)A simulation and experiment were conducted to evaluate the effectiveness of flooding control systems over different return periods and found that green roofs significantly reduce surface water discharge. (Huber, 2004)Use a photo model to simulate urban water discharge using pollution control systems.They used the IDEAL model to simulate the effectiveness of systems after developing websites (Hayes et al., 2008), (Lancaster, 2008) Langster invented the WWHM3 Pro model which helps in determining the size of control systems before design without complex calculations or continuous simulation which facilitates the implementation of LIDs (Ackerman and Stein, 2008).As the application of God guides him simulation expanded, challenges emerged related to the bias of internal output models, for example: (Alfredo et al., 2010) they used SWWM to simulate the properties of green roofs under the influence of different rainfall intensity, where the green roof runoff coefficient ranges between 0.2 and 0.7. However, the simulation was based on assumptions without calibrating the measured data. Using (Barco et al., 2008), SWMM to simulate the Ballina Creek watershed and calibrated the model using actual rainfall and length data.Permeability in the catchment area is the entrainment of depressions in impermeable areas. It is the most sensitive parameter according to the sensitivity analysis of model parameters, while the Manning coefficient is the least sensitive (Barco et al., 2008). Hydrological migration of LID systems was studied using the

DRAINMOD model by (Brown et al., 2013). (Brath et al., 2006) He also did the method of evaluating design floods by utilizing hydrological models based on long-term simulation results was summarized by (Boughton and Droop, 2003) of Australia. The impact of roof greening in New York City was analyzed by (Ostroff, 2005), while (Lee, 2005b)simulated the rainfall discharge on the surface of roads. Both studies employed SWMM. The evaluation of the effectiveness of LIDs was emphasized during the study, and the comprehension of LIDs was deepened; however, the management philosophy and technical system are still not sufficiently developed. For example, (Zhen and Yu, 2001) employed AGNPS to simulate the LIDs at the site, sub-catchment, and catchment area levels, assess the efficacy of LIDs, and suggest an optimization strategy that minimizes costs per unit of pollution load (Zhen et al., 2006, Zhen and Yu, 2001, Zhen et al., 2010). Engineering designers are confronted with the challenge of selecting the most effective measures from a vast array of LIDs when selecting and designing them. Consequently, (Pomeroy et al., 2008) implemented the AHP method to identify the LIDs and developed a fundamental decision-support system predicated on the simulation results to compare the LID design cost.

2.13 Simulation Studies on Low Impact Developments (LID)

Numerous simulation studies on LID exist in developed countries, most of which are based on actual cases, resulting in their widespread application in practice. In contrast to developed countries, China's simulation of LID is not as extensively researched and has a delayed focus. The issue of urban inundation in China, exacerbated by urbanization, has resulted in significant dam damage after the 20th century.

just as developed countries have encountered urban environments, hydrology, and ecology (Dong, 2007)Fortunately, advancements in global integration have persisted in the exchange of state-of-the-art international information. An increase. Consequently, China can readily acquire knowledge from the sophisticated experience of developed countries to address the issues above. Many academicians and experts have initiated the investigation of sustainable urban development in China, which includes the promotion and simulation of LID in response to the urban storm problem (Hu, 2010).

In recent years, Chinese academics have conducted several simulation studies on RFID devices, including one at the Beijing Olympic Park., (Hou et al., 2007) Peak flow variations in drainage channels connected with a low-lying green belt and a retention pond were simulated and analyzed using SWMM. The results showed the effectiveness of these systems in reducing and delaying peak flow and peak time, which contributes to improving rainwater utilization (Jin et al., 2010) also studied the effect of low-lying green belt and porous bricks on peak flow, discharge coefficient, and delay time over different return periods using SWMM.

The results showed that peak flow and discharge coefficients were reduced by both porous bricks and low-elevation greenbelts. Therefore, in areas with high rainfall intensity, low-elevation greenbelts are more effective in managing runoff, while porous bricks are more effective in areas with low rainfall intensity. (Chen and Guo, 2022) The researchers adopted a groundwater management model to simulate the regional outlet flow before and after the development of a community in Tianjin. They also studied the influence of the low-altitude green belt and reservoir on the community's water discharge. The results showed that the green belt and reservoir can

improve the utilization of rainwater, delay the peak time, and reduce the peak intensity at the same time. (Zhao et al., 2011) method was used with SWMM software to simulate the independent drainage system and calibrate the model based on field data. The results showed that SWMM software provides an accurate representation of the performance of the stormwater drainage system in the study area, which supports decision-making related to flood control, system modernization, and maintenance. SWMM and RECARGA software were also used to achieve this (Sun, 2011). The environmental and hydrological impacts of low-impact infrastructure technologies (LID) and urbanization in the area were simulated, with sensitivity analysis of the design elements of biological retention systems on the performance of drainage regulation. The distinct effects of these technologies and optimal management practices were also explored (BMPS) . (Fu, 2012) used PC-SWMM software to simulate rainfall and flooding in the study area. The results confirmed that the total runoff coefficient is an effective objective function for calibration and validation even in the absence of measured data for model parameters. The results showed that the study area will not experience significant flooding during the return period T = 1a, 2a. However, at T = 5a, 10a the area will experience increased pipe load, water accumulation at some nodes, and an increase in total flow time ,(Wang et al., 2012)program SWMM was used to simulate the hydrological impact of LID techniques. The results showed that urbanization increased the peak in the river basin, reduced the peak time, and increased the runoff coefficient. However, the reduced-height green belts and porous bricks proved effective in reducing the stormwater drainage pressure and reducing the peak and runoff coefficients. The simulations indicate that the application of LID on-site can restore the annual peak and runoff to the pre-

development state. In addition, the results showed a significant effect of these techniques in reducing pollutants (Wang et al., 2012), In order to establish a scientific foundation for lake design and management, (Wang et al., 2008) implemented MIKE-21 to simulate the water flow in seven distinct water bodies of Lake Jinkang in China. The objective of (Chen, 2006) was to ascertain the most effective design by investigating the combined effects of a vegetation trench, a precipitation retention area, and a retention pond. In order to simulate the reduction of the average annual discharge, (Chen, 2006) implemented a cost-benefit analysis utilizing DSS.(Sheng, 2014) developed an optimization model for designing the LID. The solution was determined using a dynamic design optimization model, with the Feicui Reservoir in China as the case study. Concurrently, the standard pollutant concentration was implemented as the constraint condition, while the minimum cost was implemented as the optimal objective function. The entire study area was optimized and simulated. (Sheng, 2014) conducted parameter sensitivity analysis on TOOLBOX and employed the exchange module method to simulate the efficacy of rainfall management measures during a designed storm to investigate the impact.

Changes in water quality and source pollution. (Zeng et al., 2006) employed AGNPS to simulate the differences in the design of precipitation management measures before and after and to evaluate the efficacy of these measures. Used by (Dai et al., 2023)

2.14 Impact of Permeable Pavement and Green Infrastructure on Runoff Management

The InfoWorks program was used to evaluate the impact of improved water runoff management in residential areas. The results indicate that the use of

permeable surfaces, green spaces, and landscaped water can effectively reduce the peak runoff and regulate the runoff coefficient of this ecological community to a relatively low level. Based on data from May to June 2011, (Zhang et al., 2023) The Mike-21 program was used to simulate the fluctuations of COD ammonium nitrogen, TN, and TP in the simulated waters. The feasibility and effectiveness of Mike-21 was confirmed by analyzing the errors between the simulated and measured values. Plans for improving and conserving the simulated waters were proposed based on the results of the simulation analysis (Tang, 2010) presented the optimal rainfall and runoff management design using the SUSTAIN program to conduct comprehensive planning and management of best management practices (BMPs) measures in the study area. The SWMM and WASP programs were used by (Niu et al., 2012) to simulate the exploitation of rainfall in the simulated rivers. The results indicate that the water quality simulation of rainfall-runoff to the scenic water can be effectively addressed through the comprehensive implementation of SWMM and WASP models. (Dong et al., 2017)used the integrated tool for evaluating the proposed drainage system layout and its impact on the water environment in Huiyuan District, Shenzhen, China by integrating SWMM with the water quality model developed by the Department of Environment of Tsinghua University.

The above-mentioned numerous field studies show that although simulation studies of low-impact design systems (LIDs) have been conducted, most of them do not include model calibration and verification, but rely on experimental criteria. Therefore, the accuracy of the final simulation needs to be further verified. Many simulations are abstractions of research objects. The situation scenario is distinguished from the actual land use planning at the study site. Therefore, the simulation results of the runoff-rainfall model

are that they possess solely academic value within China and are inadequate for guiding the design and construction of Low Impact Development (LID) systems. Even subsequent to the completion of construction, ongoing reconstruction and engineering efforts are necessitated in the ensuing period. This situation results in substantial financial resource wastage and exacerbates the discord between urban planning and the urban ecosystem. An important factor contributing to the slow implementation of LID systems in China is this. In conclusion, the concept of decentralized LID systems in China is mainly based on advanced concepts and experiences in urban storm management. China's applications and practices are still in their early stages. Furthermore, most simulation studies related to LIDs are limited to assessments using single measures, which makes them unrepresentative and there is a lack of simulation studies that are widely applicable.

2.15 Bioretention/Rain Garden

Typically, the Rain Garden/bioretention is built close to residential areas or parking lots, and it is directed through inlets to enable rainfall discharge from impervious surfaces to enter the retention tank.

Areas where rainwater retention and water quality improvement are achieved involve a series of biological, physical, and chemical processes that depend on soil, microorganisms, and plants. The complete design depends on local land use patterns, environmental conditions, and soil types. Rain garden technology provides the additional environmental benefit of reducing surface runoff, delaying or lowering peak rainfall, reducing stress on municipal pipe networks, and preventing flooding. This helps protect water quality in receiving water bodies and reduces riverbank erosion. These findings are supported by a study from the University of New Hampshire

Stormwater Center (Ballestero et al., 2016). According to the data, the average retention time of a rain garden and the flood reduction rate exceeded 85% of the inlet peak of 615 minutes before the flood peak at the rain garden site in the University of Maryland field experiment. The maximum retention rate can be expressed as 50-60%. Although the rain garden mitigated the impact of heavy rains or areas of high water, it remains an effective means of flood control. Most of the initial research on rain gardens was conducted in laboratories (Davis et al., 2009). Studies have indicated that rain gardens can significantly reduce copper, lead and zinc concentrations by more than 90%. In experiments, retention rates of copper, lead and zinc in snowmelt water can reach 89% and 99%, respectively. However, it is important to note that the ability of rain garden media to absorb heavy metals is limited. Heavy metal accumulations can reach levels that pose a health risk after 15 to 20 years of use. Periodic soil restoration and selection of appropriate plant species can reduce the amount of accumulated heavy metals. Research has shown that metal retention is highly correlated with the organic matter content of the soil($P<0.01$). In general, plants absorb heavy metals, accounting for 0.5-3.3% of the total metal retention. However, due to the variety of plant species used, the amount of heavy metals absorbed by plants in a Norwegian study may represent (2-8%) of the total heavy metals retained in the retention area (Dietz, 2007). Rain garden design specifications have not yet been standardized. However, research on rain gardens can provide a more comprehensive understanding of the mechanism of pollutant retention. Retention areas are very effective in reducing stormwater runoff and concentrations of many pollutants, as well as reducing phosphorus runoff and total nitrogen retention problems. However, long-term field experiments are still needed to collect data that will allow the

performance of these systems to be evaluated in different seasons and over time. The use of alternative media or designs requires further research into methods of reducing specific pollutants. Several rigorous studies have been conducted on the effectiveness of mineral and nutrient retention in rain garden systems, but bacterial treatment and water temperature reduction still need further research (Dietz, 2007). The replenishment and preservation of the basin's base flow and groundwater are critical objectives for implementing rain garden technology. Nevertheless, there are few investigations on related mechanisms, and this function is not widely considered in applications. It is imperative to gradually establish the corresponding design criteria in future research and application. This includes the design of the annual runoff volume to preserve the hydrological status before development, the optimization of groundwater recharge through biological retention systems, and the consideration of the natural subsoil when recharging the groundwater. In particular, areas where groundwater recharge is a concern should be focused on (Dietz, 2007).

2.16 Identification of research gaps and the necessity of this study

The existing literature on the impact of climate change and urbanization on runoff or flooding volume reveals numerous research deficiencies and emphasizes the necessity of additional investigation. The discussions we have had have revealed several significant findings and knowledge deficits. Climate change and concurrent urbanization require a deeper understanding of runoff dynamics and flood magnitude, highlighting the need for innovative drainage systems. These two factors have a complex impact on runoff generation, calling for the study of their combined effects to ensure effective water management and reduce flood risks. A review of

the literature indicates a clear lack of studies on flood control and urban hydrology, emphasizing the need for local research to explore the opportunities and challenges associated with climate change and urban expansion in specific areas. The effectiveness of low-impact strategies has not been adequately investigated LID Existing studies are limited to a preliminary assessment of their control factors, calling for further research to analyze their performance in reducing runoff and flood risks. In addition, studies emphasize the importance of integrating surface water management measures with existing infrastructure to enhance their efficiency. There are two major research gaps represented by the absence of effective solutions and the limited focus on recent flood events, especially in Karbala. Although Shiraz has been exposed to severe climate disasters in recent years, highlighting its vulnerability to climate change, Karbala requires in-depth studies to understand the direct climate impacts on floods and identify the most appropriate strategies to mitigate their future effects. Consequently, the proposed thesis addresses these research voids by emphasizing localized studies that evaluate the influence of climate change and land use on the volume of runoff or flooding.

2.17 Summary

This chapter deals with previous studies on which the thesis was based, which deal with the importance of managing rainwater and surface runoff in urban areas, as well as the impact of urbanization and climate change on the hydrological cycle. The chapter indicates that surface runoff arises as a result of rainfall falling on hard surfaces such as roads and impermeable surfaces, and thus leads to the transfer of pollutants and the deterioration of

water quality. Poor management of surface runoff increases the risk of pollution, erosion and flooding.

Urbanization increases impermeable areas, causing increased runoff and reduced infiltration. Floods occur naturally, but poor drainage systems increase their impact, destroying infrastructure and increasing health risks. Sustainable management techniques, such as green infrastructure and low-impact development (LID), are addressed, which aim to reduce discharge and improve water quality. These techniques include rain gardens and permeable pavements, which help filter water and reduce pollution. Studies have shown that these methods are effective in reducing runoff and pollutants.

Also, based on many studies, the efficiency of modeling has been proven by using a rainwater simulation model (SWMM), as it can be relied upon to model urban floods and determine the locations and sizes of floods in networks.

Chapter Three: Methodology

3.1 Introduction

This chapter deals with the process of collecting hydrological and hydraulic data for the rainwater drainage network in the Al-Wafaa neighborhood in Karbala and analyzing the network through a rainwater network simulation model SWMM. It also discusses the negative consequences of land use changes resulting from urban expansion and climate change, as all of these reasons have negatively affected the amount of water entering the network and the amount of surface runoff. It also discusses the alternatives used to reduce flooding resulting from the aforementioned causes. This chapter also explains how to enter data and characteristics into the program and the research methodology followed.

This chapter is divided into:

First: Description of the study area: This includes identifying the characteristics of the studied area, such as topography, slope, land use patterns, and total area, in addition to the characteristics of the sub-basins, including area, width, permeability, and seepage.

Second: Description of data related to hydrological processes such as rainfall data and its duration.

Third: Description of data related to hydraulic processes, which includes the characteristics of the basic elements of the rainwater network, such as drainage outlets, pipes, and pumping stations.

Fourth: Description of the physical model (SWMM) used to simulate the hydrological and hydraulic data, with an explanation of the mechanism for

directing the model to create a realistic simulation and evaluate the performance of the rainwater drainage network.

Figure (3-1) shows the methodological scheme followed in this study

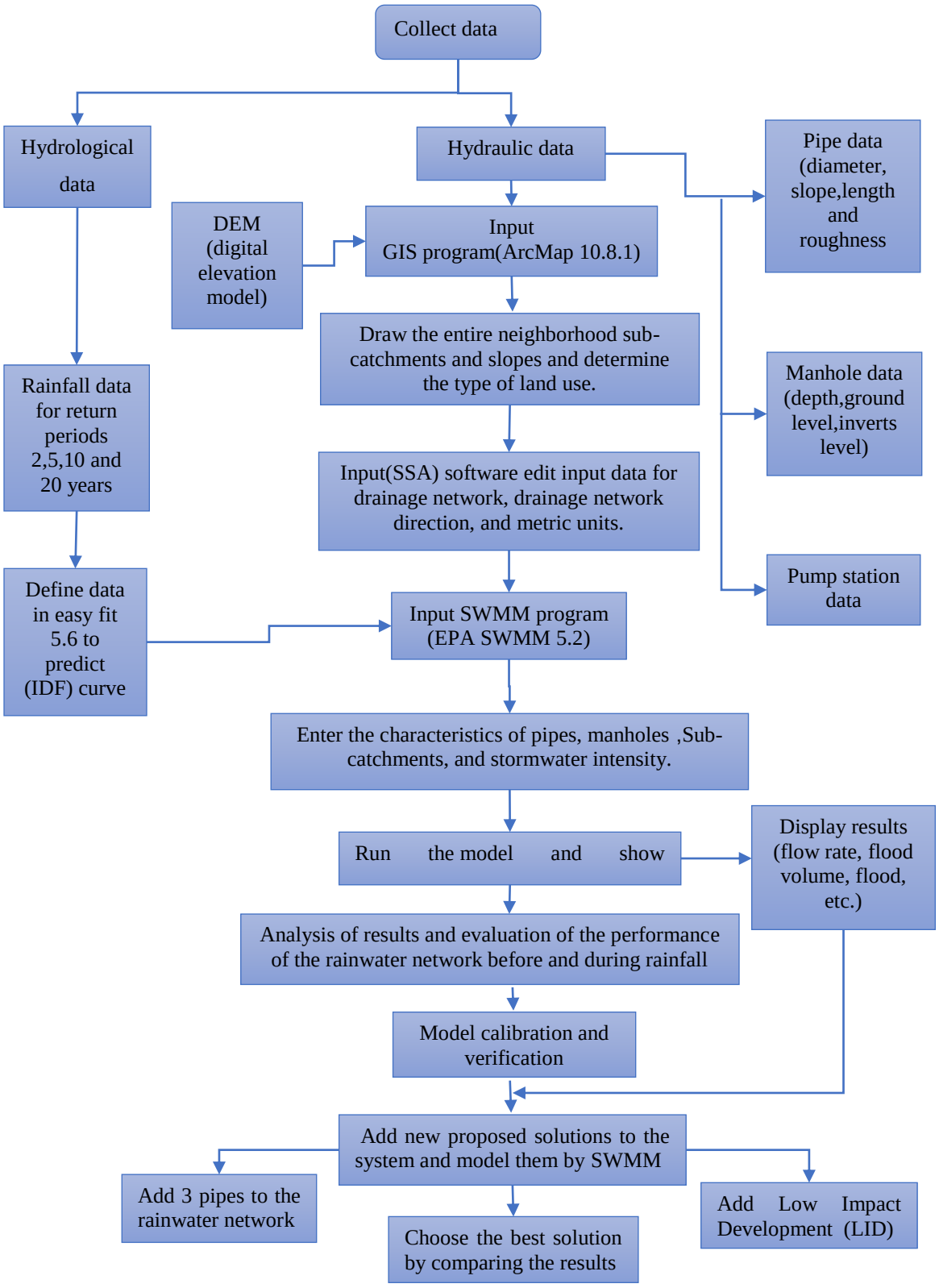


Figure 3-1 flowchart working methodology.

3.2 Study area

Al-Wafaa neighborhood was selected, as shown in Figure (3-2). It is located northeast of the center of Karbala Governorate, Iraq.It lies between latitudes (32° 33′ 30″–32° 34′ 10″) N and longitudes (44° 1′ 20″–44° 1′ 50″) E .The selected area was flat, with a moderate slope and sandy clay soil. Its regional elevations ranged from 2.2 meters above sea level. It is located 2 km from the center of Karbala Governorate. The total area is about 0.701 square kilometers. The previous area, which includes green spaces and unpaved areas, constitutes about 30%. The unimplemented area, which represents roofs, paved areas, and sidewalks, constitutes about 70% of the total area. There are 237 subcatchment within the rainwater drainage network used in the case study. The study was conducted in the city of Karbala, Iraq. The study area is located about 100 km southwest of the capital, Baghdad (Farhan et al., 2018), specifically in the Al-Wafaa neighborhood. The study uses historical data from the system to analyze the maximum daily rainfall over 40 years for the Karbala Meteorological Station. Hydrological information for the research area was obtained from the Iraqi Seismic Authority and the Meteorological Office. This data includes daily rainfall (mm). The Karbala Sewerage Directorate [DSK] provided the hydraulic data, along with information on soil properties, topography, land use, and a digital map of the research area. This contains information on rainfall networks, research area characteristics, sewer openings, pipelines, and all their accessories. When the maximum rainfall corresponds to the study area, the maximum rainwater flow is considered.

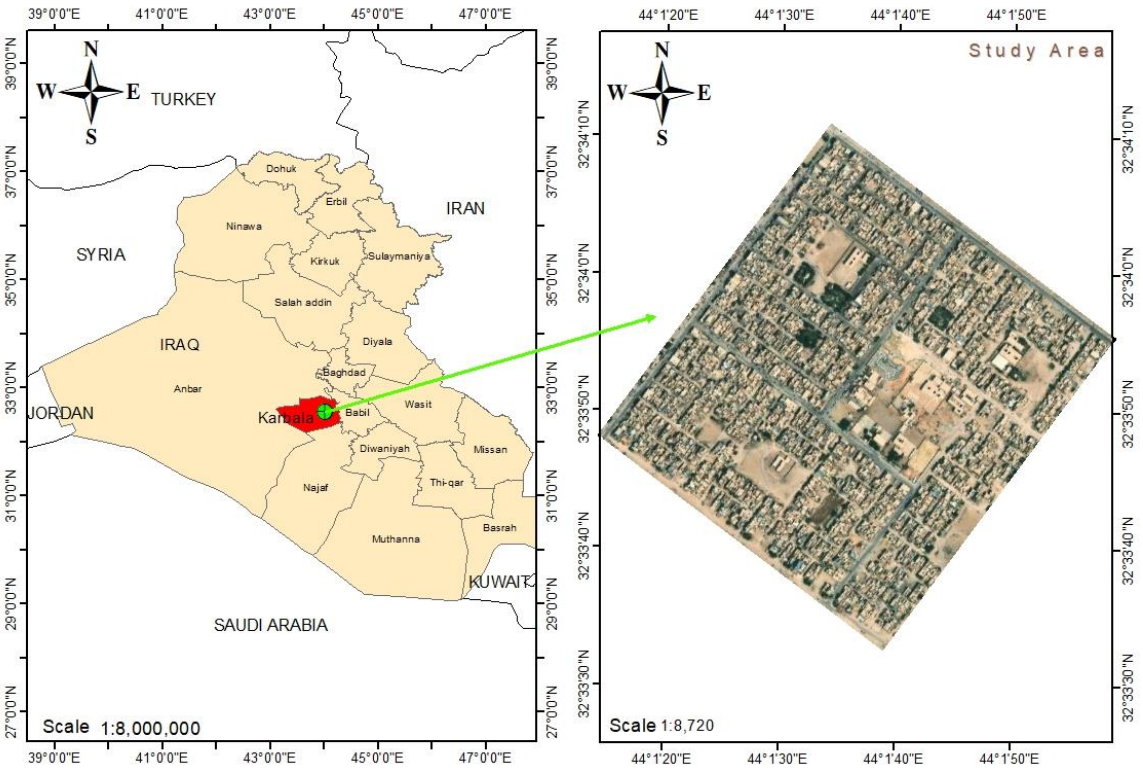


Figure 3-2 Al-Wafaa neighborhood in Karbala, Iraq (created by ArcGIS 10.8.1 and Google Map, 2024).

3.3 Data collected

3.3.1 The topographic

The topographic map was created using ArcGIS 10.8.1 and contains a slope map calculated using ASTER DEM data from (USGS, 2018), where the lower the slope value, the flatter the land and vice versa. Randomly distributed points were generated for the study area by retrieving the digital elevation model (DEM) file in the GIS program. Elevation values were then extracted and applied to these points, resulting in points containing coordinates (X, Y, Z). The Arc toolset is part of the GIS software package. The land of Karbala, specifically the Al-Wafaa neighborhood, is

characterized by very gentle slopes, as shown in Figure (3-3) Slope map of the study area.

The figure shows that the average slope of the study area is equal to 0.5%

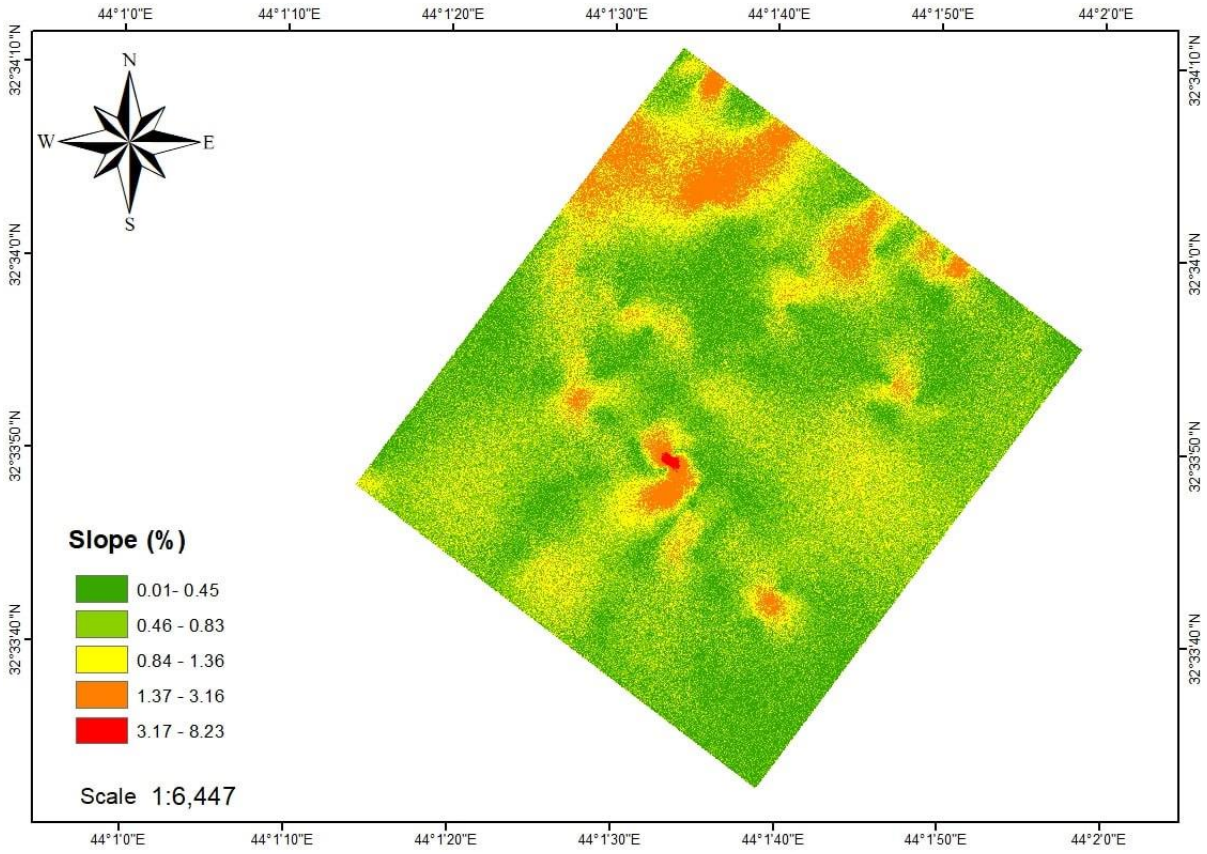


Figure 3-3 Slope Map of Al Wafaa Area Generated by GIS Software Based on DEM

.

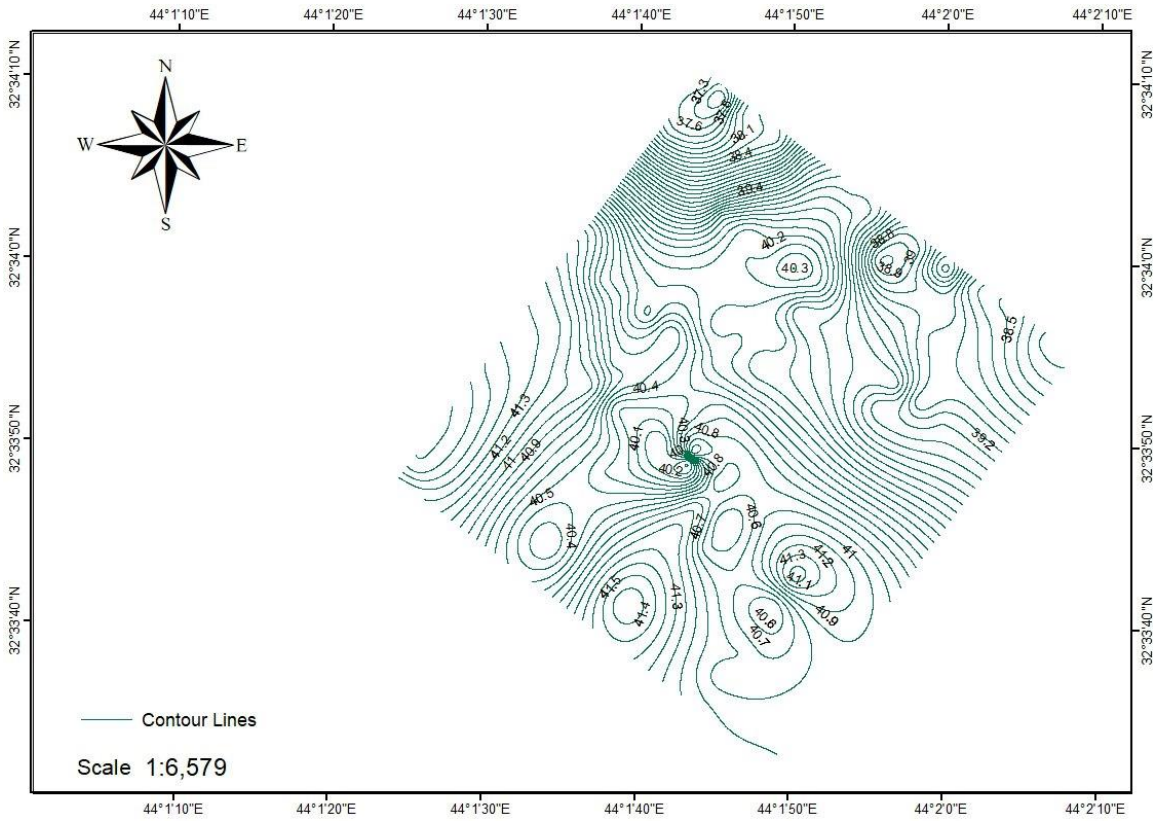


Figure 3-4 The contour map of the study area was created using a geographic information system(GIS) based on digital elevation model data (DEM).

Figure (3-4) shows the control map of the study area (Al-Wafaa neighbourhood), which shows the contour lines. The study area's elevation ranges between 2.2 meters. The map was created using the Geographic Information System (GIS) based on Landsat (multi-wavelength) data with an accuracy of 30 meters, sourced from the US Geological Survey (USGS) in cooperation with NASA. This map was instrumental in evaluating the gradients of each sub-catchment in the study area.

3.3.2 Land use

Al-Wafaa district is considered a residential district, with 80% housing, 12% gardens and service buildings, and 8% paved roads. The

figure (3-5) also shows the type of land used in the study area in detail, whether residential, educational, commercial, green, or industrial.

Figure 3-5 Al-Wafaa Quarter's land use in Karbala, Iraq.

3.3.3 The hydraulic data

The Karbala Sewerage Directorate collected the hydraulic data for the Al-Wafaa neighborhood. It contained the Al-Wafaa neighborhood network, which includes pipes and manholes and their characteristics. The GIS program represented these as point maps and lines.

3.3.4 Hydrology data

Hydrological data refers to historical data on daily precipitation for 40 years (1984-2024), which is obtained from satellite data sourced from the Global Energy Resources Forecasting Project (POWER) from the National Aeronautics and Space Administration (NASA) research (https://power.larc.nasa.gov/).

Researchers rely on reliable alternative sources, as mentioned above, to obtain daily weather data due to the incompleteness of daily data from rainfall gauges.

This data was collected based on information from the meteorological station in Karbala, located at coordinates 32° 34′ 12″ N and 44° 3′ 0″ E and an altitude of 29 m above sea level.

Figure (3-6) shows the observed daily rainfall data, where the annual rainfall rate was about 80 mm. Rainfall data are used to develop IDF curves.

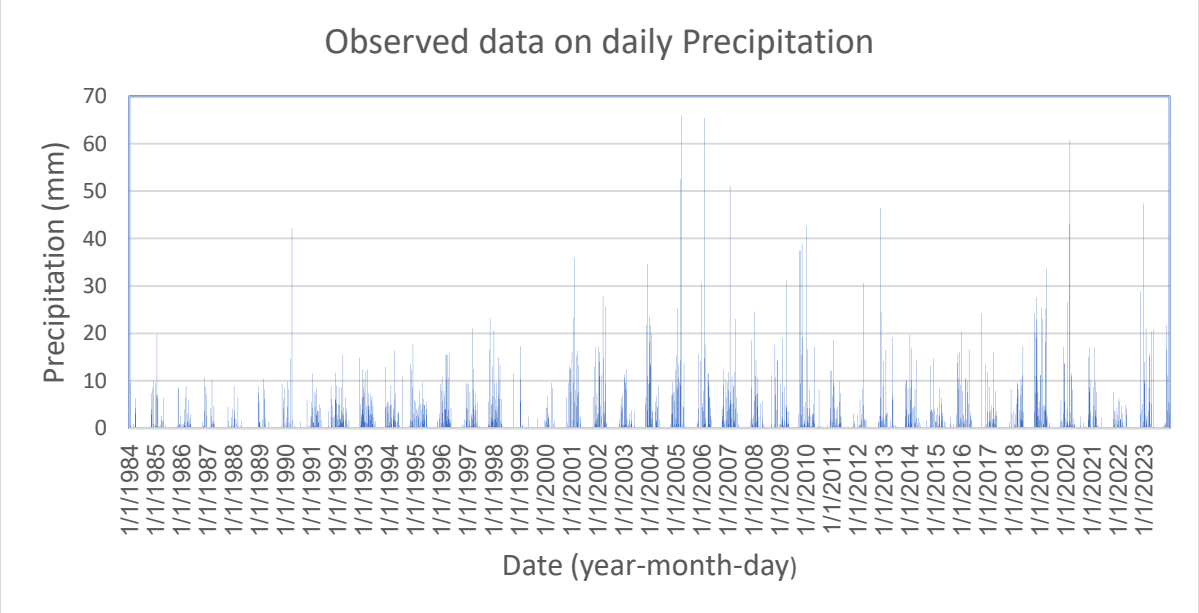


Figure 3-6 Annual rainfall data for Karbala city station for the period (1984 - 2023)

3.3.5 IDF Curves

Intensity-duration-frequency (IDF) curves are a standard tool in flood estimation for various engineering projects, playing an important role in most water resources engineering projects. The development of IDF curves is based on rainfall data, which requires the availability of an accurate historical series of maximum rainfall intensity values for different time periods. Rainfall measurement is essential for estimating surface runoff, especially in urban areas with short rainfall duration. In Iraq, rainfall duration is short, and most available data are daily. The goal of generating IDF curves is to develop empirical equations that estimate the design rainfall intensity for modelling the rain drainage system (SWMM). This method allows for estimating the maximum rainfall values for recurrence periods of 2,5,10,20 years and periods shorter than one day so that data are extracted every 5 minutes based only on daily data.

The model is based on the simple gradient hypothesis, which assumes the existence of indirect relationships between different recurrence periods and rainfall duration, which allows for deriving IDF relationships from long-term data. In this study, the Easy Fit 5.6 program was used to analyze rainfall data recorded over 40 years (1984-2024), and the data were represented through IDF curves for the specified periods. The maximum rainfall intensity values during the different recurrence periods were determined using the standard Gambel method (Standard Gamble Method) to obtain accurate IDF curves.

The probability of rainfall per minute was determined using the Easy Fit 5.6 program with recurrence periods of 2,5,10,20 years in addition to using the Gumbel distribution. The Gumbel distribution (EV-1) is the first extreme

distribution tool used to estimate the distribution of maximum or minimum values of a variety of distributions. This distribution is commonly used to estimate IDF curves due to its high accuracy in modeling extreme events. Extreme events are employed in the Gumbel distribution, which is nearly straightforward (Lee, 2005a).

Sherman's equation 3.1 (Nhat et al., 2006) showed that rainfall intensity decreases with increasing rainfall duration over a given return period. This empirical equation has been widely used in practical applications of hydrology. In the present study, the equation is used to estimate rainfall intensity for a given return period :

$$\boldsymbol{i} = \frac{\boldsymbol{a}}{(\boldsymbol{T}+\boldsymbol{b})^{\boldsymbol{c}}} \text{-3.1)}$$

The constant parameters (a, b, and c) are associated with the metrological conditions, while (i) denotes the rainfall intensity in mm/hr. The duration (T) is defined in minutes.

3.4 Simulation Setup for SWMM

3.4.1 SWMM model

SWMM is an analysis and design simulation program for stormwater networks. The Environmental Protection Agency devised it in 1971 in the United States (Rossman, 2010).

(Rangari et al., 2018) Implemented SWMM to replicate the quantity and quality of sewerage systems across a variety of return periods. A comprehensive collection of data was conducted for the Al-Wafa neighborhood, including pipelines, floor areas, and inspection manholes, as

well as service data, green spaces, and their unique characteristics. Employed SWMM.Comprehensive data was collected on the Al Wafaa neighbourhood, including pipes, land areas, manholes, green areas and their characteristics, and service data. Raster map files and polygons were used in lines to display the data in the ArcMap GIS program. Amendments and corrections were made to the data after loading the network in the SWMM program. The surface water drainage model in the SWMM program directs the output through a network of pipes and lines. The water quality of each conduit and/or channel is maintained at various points during the simulation, and the flow rate, flow profundity, and volume of the resultant discharge within each sub-catchment are preserved by SWMM. It also performs hydrological analysis and provides data entry and simulations for the study area. The software environment can be used to simulate hydraulics and water quantity and to analyze the results in various formats. The SWMM simulation's input and output data are illustrated in Appendix A below. Some of the tools that are accessible in SWMM include color-coded drainage and conveyance maps, profile graphs, statistics, Frequency charts, and tables, in addition to sequential charts and timelines. (Rossman, 2010). For the SWMM simulation program, GIS 10.8.1 was employed as the instrument to prepare the input data.

3.4.2 Modeling Hydrology Data

3.4.2.1 Rain Gage

Rain gauges are tangible objects that simulate drainage systems and provide rainfall data for sub-catchment regions, field studies, and rainfall data. is indispensable for the Storm Water Management Model (SWMM), as precipitation is the primary determinant. Models necessitate input attributes

such as source name, recording period (e.g., hourly, 15-minute), and data types (such as density, volume, and cumulative volume) to comprehend and oversee drainage systems in various locations (Rossman, 2010).

According to the catchment response, rainfall fluctuations necessitate a specific time interval. Rapid response times are observed in small, steep catchments, while delayed in vast, flat catchments.

Data is utilized as (start of interval) values in SWMM rainfall Time Series, assuming that rainfall intensity or depth commences at the beginning of its associated date/time value and persists for the duration of the gage's recording interval. A storm duration is arbitrarily selected or aligns with the estimated catchment time of concentration (tc), where the outflow is equivalent to a constant proportion of continuous rainfall or outflow is equivalent to rainfall on a catchment with no losses (James et al., 2010, Rossman and Huber, 2016a).

The installation of rain gauges is to gather precipitation data for one or more sub-catchment areas presently being studied. Rainfall data may be gathered using a user-defined time series or an external file.

A standard user-defined format and a variety of widely used rainfall file formats are both compatible with it (Rossman, 2010). The primary input properties of the rain gauge are as follows:

1. Rainfall classifications such as intensity or volume.
2. Time periods (e.g. five minutes spread over hours).
3. Acquisition of precipitation data (either through the importation of an external file or by inputting a time series).
4. Designation of the rainfall dataset source.

In this analysis, return periods were correlated with Rain Gauge 2, Rain Gauge 5, Rain Gauge 10, and Rain Gauge 20. Sub-catchments' Physical Characteristics

Al-Wafaa district, with a total area of about 0.701 km^2, was divided into 237 sub-catchments, each ranging from 400 to 2600 m^2. Sub-catchments that discharge into MR-44 through manholes were mapped in this study through a field survey of the study area during rainfall, and these areas were identified. According to the groundwater management model, sub-drainage basins are ideally conceived as rectangular, spatially aggregated, non-linear reservoirs, and their outflows are directed to the sub-drainage basin's outlet (James et al., 2010). Consequently, the Al-Wafa neighbourhood was partitioned into 30% permeable and 70% impermeable surfaces. Surface runoff is directed to a single drainage site through hydrological land units characterized by topography and drainage system components. They are typically selected to align with various land uses and simplify parameter estimation. In both permeable and impermeable areas, the designated rainfall gauge, outlet node or sub-basin, designated land use, sub-drainage area, impermeability, slope, characteristic width of surface flow, and Manning's coefficient of surface flow are among the key input parameters for a sub-drainage. The proportion of impermeable areas that do not contain depression storage and depression storage in both permeable and impermeable areas are additional input parameters (James et al., 2010, Rossman, 2010, Rossman and Huber, 2016a). Figure (3-7) shows the division of the research area into 237 sub-catchments.

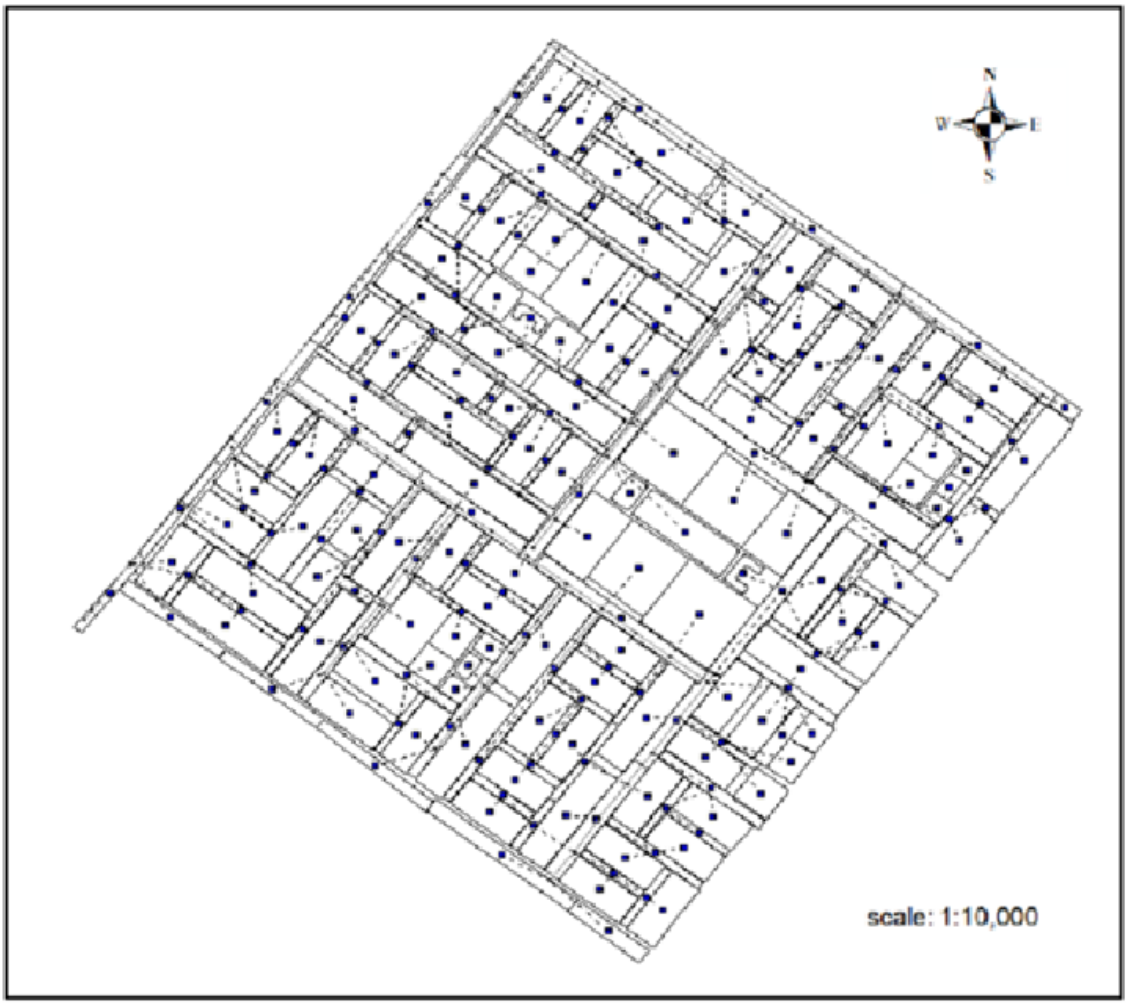
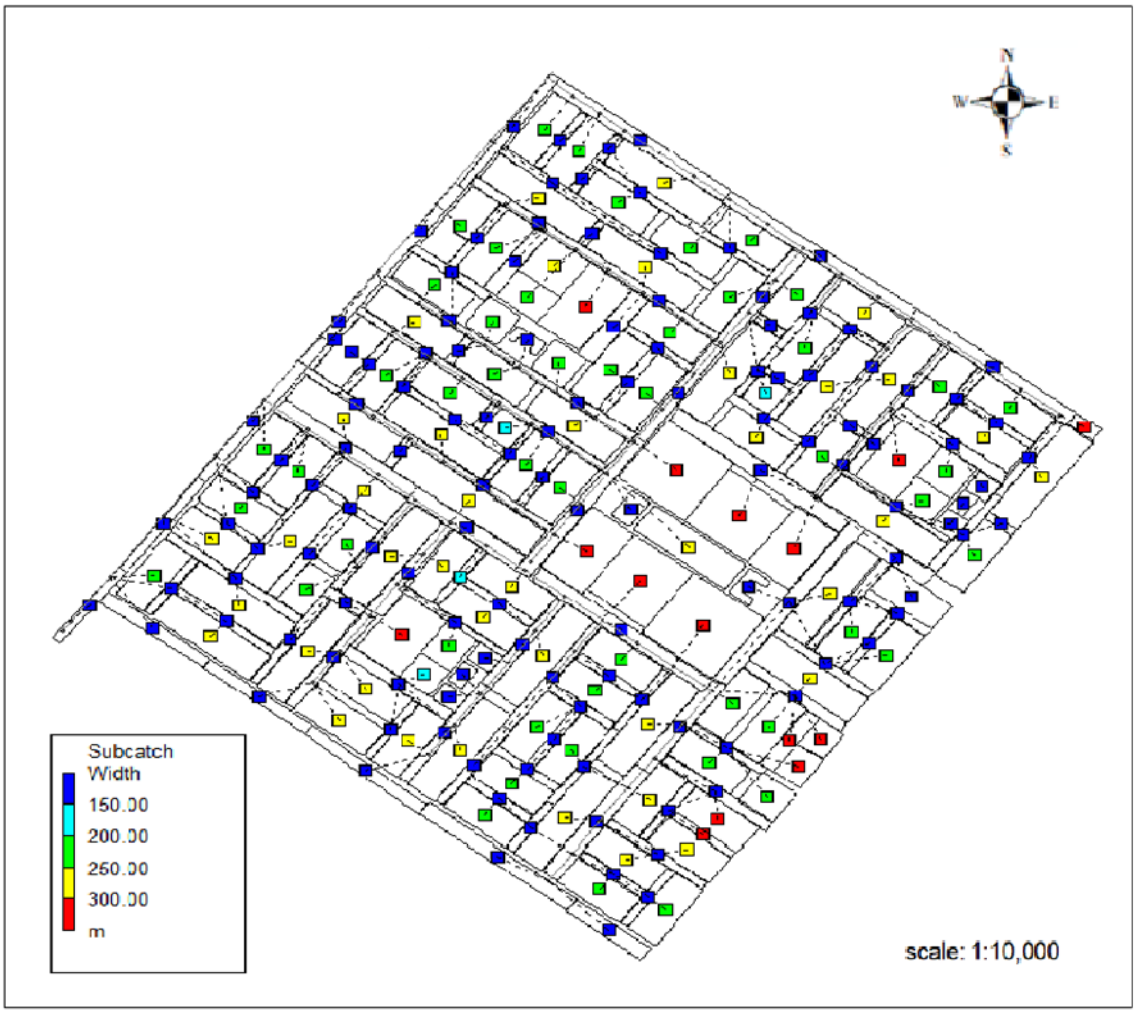


Figure 3-7 Subcatchment Areas of the Study Area by Using SWMM

- **Area and width for sub-catchment**

The Karbala Sewerage Directorate provided the aerial image, and the map illustrates the spatial distribution and facilitates the estimation of the sub catchment area through the use of the measurement tool in the GIS program. 400 to 2600 m^2 is the size of the sub-catchment in the Al-Wafa neighbourhood . Because the width of the drainage basin has no tangible importance (Canton and Schmidt, 2011). (Cantone and Schmidt, 2011), the

value of width was determined by the length and area of the surface runoff (James et al., 2010, Rossman and Huber, 2016a). Figure (3-8)shows the division of areas to calculate the width for each area shown in the figure.



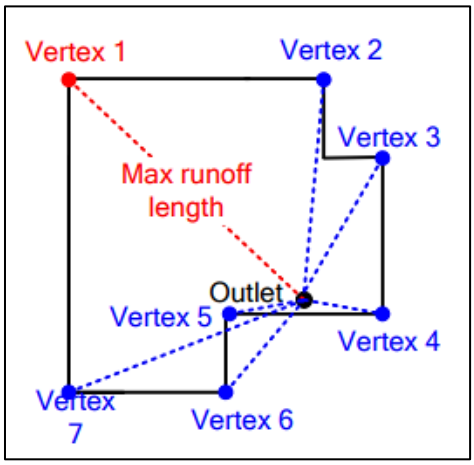


Figure 3-9 Determine the maximum length of a surface runoff (Shen and Zhang, 2014)

Figure (3-9) (Shen and Zhang, 2014) Illustrates the process in which an arbitrary point is defined as the most distant location from the outflow and should correspond to one of the heads of the sub-catchment. The width of the sub-catchment was determined by calculating the area of the sub-catchment and the surface flow path. The results indicated that the width of

Figure 3-8 Width of Study Area Subcatchments by SWMM

the sub-catchment area ranged from 9 to 339 m.

The sub-catchment width is determined by dividing the area by the longest surface flow path, as determined by equation (3.2) (Rossman, 2010).

$$W = \frac{A}{Lmax} \qquad \text{……..(3.2)}$$

where:

W: width of the sub-catchment (m),

A: sub catchment area (m^2), and

L max.: maximal runoff length in sub-catchment (m); this value is determined by calculating the distance between each vertex and the outlet point, as illustrated in Figure (3-9) (Shen and Zhang, 2014).

The slope of the catchment

According to (James et al., 2010)The idealized sub-catchment slope is perpendicular to its breadth. The tendency of the fluvial flow surface is the cause. The average surface slope of 0.5% for each sub-basin was determined by subtracting the ground elevation of the manholes in the downstream area from the ground elevation of the manholes in the upstream area and then dividing the result by the distance between them.

Permeable and impermeable surfaces

Impervious and previous are the two sub-area options available for each sub-catchment in SWMM modeling. As illustrated in Figure (3-10) , the sub catchment properties table includes these options and other option, such as sub catchment routing and per cent routed.

Subcatchment Sub-27

Property	Value
Y-Coordinate	3603514.365
Description	
Tag	
Rain Gage	raingage1
Outlet	hr34a
Area	0.559215
Width	254.744
% Slope	0.5000
% Imperv	75
N-Imperv	0.011
N-Perv	0.15
Dstore-Imperv	2.54
Dstore-Perv	5.08
%Zero-Imperv	25
Subarea Routing	OUTLET
Percent Routed	100
Infiltration Data	GREEN_AMPT
Groundwater	NO
Snow Pack	
LID Controls	0
Land Uses	0
Initial Buildup	NONE
Curb Length	0
N-Perv Pattern	
Dstore Pattern	
Infil. Pattern	

Figure 3-10 The SWMM modeling sub-catchment properties table. Impervious, outflow, and pervious are the three options currently available in sub-area routing.

Figure 3.10 demonstrates the typical impact of these three sub-catchment routing discharge methods on an individual sub-catchment.

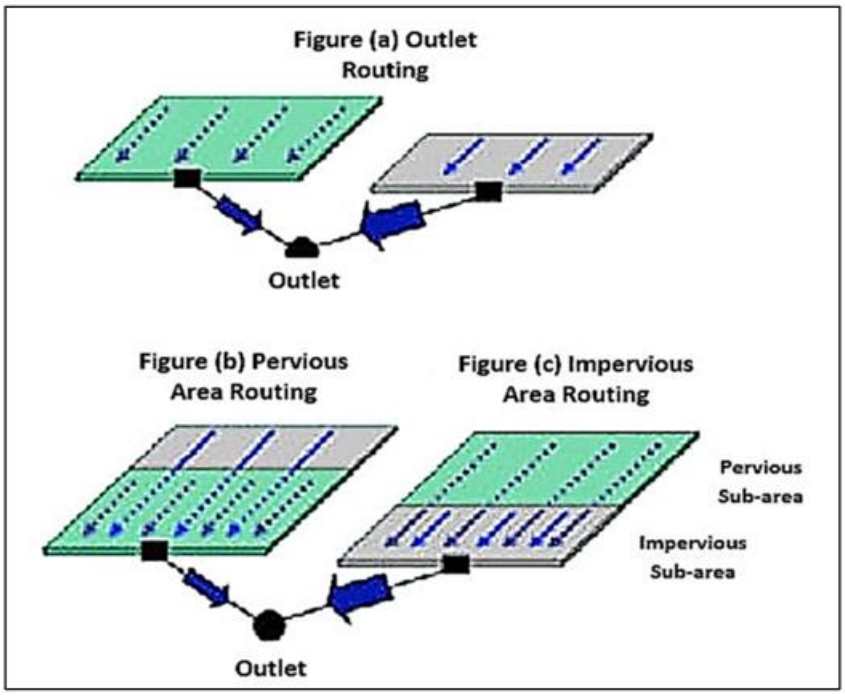


Figure 3-11 The SWMM sub catchment segments (Gironás et al., 2009)

Figure (3-11) (a) illustrates the outlet option, which directs the drainage from both sub-areas to the sub-catchments outlet. The %zero-impervious value will be zero, as the impervious area entirely provides the runoff. In this case, however, the outlet or the impervious area will receive 100% of the runoff. Figure (3-11) (b) illustrates the previous option, which directs the impervious catchment runoff to the outflow via the previous sub-catchment. This method results in the loss of part of the water flow due to infiltration and storage in the depressions in the previous areas. Figure (3-11) (c) illustrates the impervious options, which transit through the impervious sub-catchment to divert the discharge from the preceding sub-area to the outflow.(Gironás et al., 2009).

It was the impervious area of each sub-catchment that was initially established.

with respect to the occupation of soil by pavements and roofing. For impervious areas, SWMM exclusively employs depression storage (dp) losses. Permeable sub-catchments, impervious sub catchments, and previous sub-catchments are the three categories into which sub catchments in Karbala City are divided. Sub-catchments that are impervious can be classified into two categories:

1) Impervious surfaces and

2) permeable surfaces were the two categories into which the sub-catchment areas were divided. As a result, the impervious area is further divided into two distinct areas: one that contains depression storage and the other that does not. Most of the rainfall is converted to runoff in the street or flow in the pipelines, while the impervious area is limited to the depression storage. However, the upper soil zone is a potential entry point for runoff from the preceding region (Rossman, 2010).

Future sub-streams are indirectly affected by the proportion of impervious surfaces, while local surface water is directly affected(Chabaeva et al., 2009).The permeability-to-impermeability ratio can be calculated by dividing the impervious area by the total sub-stream area using a land use map enhanced by urban planning (DSD, 2016). The proportion of impermeable surfaces within each sub-basin in the research region varies from 70% to 95%. Table (3-1) provides the estimated percentage of impervious areas for various land uses (Panos et al., 2018). The impervious and pervious areas were selected within a range of 25% to 95% of the total study area. The percentages of impervious and pervious areas were determined based on the nature and extent of land cover (see Table 3.1 and Figure 3.5)

Table 3-1 Land Use Impervious Area Percentage ((Panos et al., 2018))

Surface Characteristics and Land Use	Imperviousness percentage (%)
Business	
Downtown Areas	95
Suburban zones	75
Residential properties (lot area only)	
Single-family	
2.5 acres or larger	12
An area of at least 2.5 acres	20
approximately 0.75 to 2.5 acres	30
0,25 to 0.75 acres 0,25 acres or fewer Apartments	45
Manufacturing	75
Industrial	
Light-coloured regions	80
Dense regions	90
cemeteries, parks	10
Sports fields	25
Colleges	55
Areas consisting of railroad yards	50
Undeveloped Regions	
historical flow analysis	2
Agriculture and greenbelts	2
off-site flow analysis (when land use is not specified)	45
Streets	
Paved	100
Unpaved Gravel (packed)	40
Driving and walking	90
Decks	90
sandy loam, lawns	2
Grass, clayey soil	2

Manning Roughness Coefficient

This parameter is one of the most effective parameters in hydrological modeling. The values for each sub-catchment depend on the type of land use. Table (3-2) presents Manning's roughness coefficient for various types of surface land (McCuen, 1989). 0.015 was the Manning roughness used in this study. Because SWMM employs the Manning equation to calculate the

overland flow rate, this value is equivalent to Manning's roughness coefficient (n).

Table 3-2 Roughness Coefficient for Subcatchments for Manning (McCuen, 1989)

Conduit Material	Manning n
Closed Conduits	
- Asbestos-cement pipe	0.011 - 0.015
- Brick	0.013 - 0.017
- Cast iron pipe	
- Cement and seal-coated	0.011 - 0.015
Concrete (monolithic)	
- Smooth forms	0.012 - 0.014
- Rough forms	0.015 - 0.017
- Concrete pipe	0.011 - 0.015
Corrugated Metal Pipe	
- 1/2 in. (13 mm) - 22/3 in. (68 mm) corrugations	
- Plain	0.022 - 0.026
- Paved invert	0.018 - 0.022
- Spun asphalt	0.011 - 0.015
Plastic Pipe (Smooth)	0.011 - 0.015
- Polyethylene	0.011 - 0.015
- Polyvinyl Chloride	0.009
Vitrified Clay Pipe	
- Vitrified clay	0.011 - 0.015
- Liner plates	0.011 - 0.020

Depth of Depression Storage (dp)

The depression storing levels in impervious and pervious areas are critical characteristics presented in Table (3-3) (Federation and Engineers, 1992)The depression depth for each sub-catchment of impervious surface is 2.54 mm, while the depth for pervious surfaces is 5 mm.

Table 3-3 Depth of depression storage for various land uses(Federation and Engineers, 1992)

Surface Characteristics	Depression Storage
Impervious surfaces	0.05 - 0.10 inches
Lawns	0.10 - 0.20 inches
Pasture	0.20 inches
Forest litter	0.30 inches

3.4.2.2 The Infiltration Model

The infiltration method, which expresses the process of water penetration from the surface of the earth into the soil, is an essential part of groundwater management models SWMM and is widely used in soil sciences and hydrology. In this research, the Green-Ampt methodology was adopted to estimate the infiltration rate, as it is based on physical foundations, which makes it different from purely empirical models such as the curve number or Horton techniques. In many cases, this methodology shows a high ability to accurately represent the actual soil infiltration through approximate solutions. The Green-Ampt equation requires the determination of three basic parameters to be applied to a specific type of soil:

K: Hydraulic conductivity at saturation (mm/hr)

Ψ : Suction head (mm)

FC: Infiltration capacity. (mm/hr).

Φ: Porosity of the soil.

According to (Rossman, 2010) , the values of these parameters are determined as shown in the table (3-4).

Table 3-4 Variations in Green Ampt parameters for various soil types(Rawls et al., 1983)

Soil Texture Class	k (cm/hr)	Ψ (kPa)	ϕ (cm^3/cm^3)	FC (cm^3/cm^3)	WP (cm^3/cm^3)
Sand	4.74	1.930	0.437	0.062	0.024
Loamy Sand	1.18	2.400	0.437	0.105	0.047
Sandy Loam	0.43	4.330	0.453	0.190	0.085
Loam	0.13	3.500	0.463	0.232	0.116
Silt Loam	0.26	6.690	0.501	0.284	0.135
Sandy Clay Loam	0.06	8.660	0.398	0.244	0.136
Clay Loam	0.04	8.270	0.464	0.310	0.187
Silty Clay Loam	0.04	10.630	0.471	0.342	0.210
Sandy Clay	0.02	9.450	0.430	0.321	0.221
Silty Clay	0.02	11.420	0.479	0.371	0.251
Clay	0.01	12.600	0.475	0.378	0.265

Green-Ampt rate equation 3.3 is presented below (Rawls et al., 1983, Rossman, 2010, Rossman and Huber, 2016b).

$$f = K\left(1 + \frac{n\Psi}{F}\right) \qquad \ldots\ldots. \ (3.3)$$

Where:

f: Infiltration rate (mm/hr.)

K: Saturated hydraulic conductivity (mm/hr.)

Ψ: suction head at the infiltration wetting front (WP), (mm)

n: Available porosity

F: Infiltration amount (mm)

The coefficients of the equations Green-Ampt were included in the model SWMM. The values of these coefficients depend, according to (Rawls et al., 1983) on the type of sediments in the studied area. In this research, sandy soil was chosen, and the coefficients used were applied to all sub-watersheds. The values are shown in Figure (3-12).

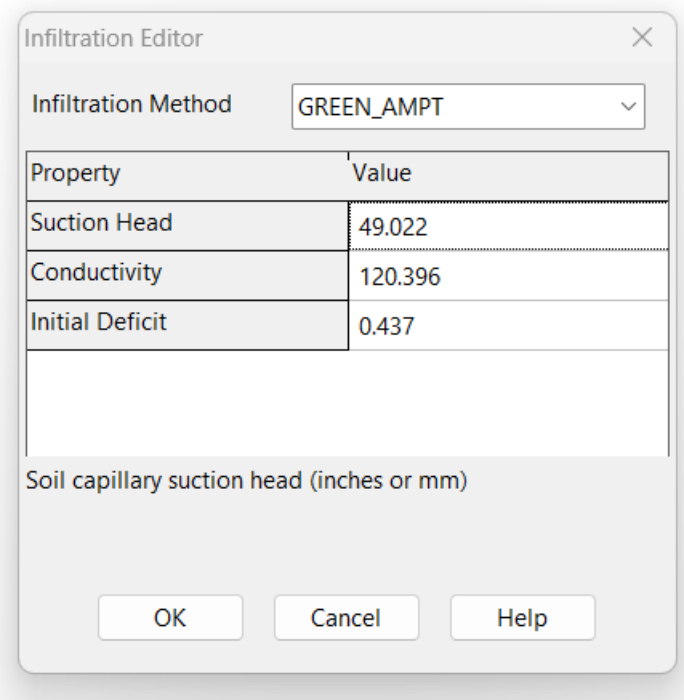


Figure 3-12 Green ampere factor for each subcatchment.

The optimal model for infiltration remains the subject of debate. The Horton model has a lengthy history of use in dynamic simulations. In contrast, the Curve Number model is derived from the well-known SCS Curve Number method for simplified runoff models. The equation of the Green -Ampt model, which is more physically based, provides a comprehensive description of the infiltration process (James et al., 2010).The soil type in the study area is sand, with a suction head of 1.93 in, an initial deficit of 0.437 in, and a conductivity of 4.74 in/hr.

3.4.2.3 Runoff from the Surface

By the time the depth of the reservoir exceeds the irregularity of the ground, surface runoff develops into overland flow and ponding on saturated sloping surfaces (Rossman, 2010). Two primary mechanisms can induce surface saturation:

• Above-ground saturation (Hortonian overland flow), which is significant in the event of severe rainfalls, dry catchment conditions, low soil conductivity, and impermeable urban regions, which have the potential to generate overland flow.

• below-ground saturation, in which the groundwater table rises to the ground surface, thereby restricting water inflow (Tikkanen, 2013).

Over time, surface water flow may gradually increase until it reaches saturation, covering the entire surface of the catchment. Although rainfall does not always produce surface runoff, the actual amount of precipitation represents the portion that causes runoff immediately or after a short period without the need for evaporation or groundwater storage (Tikkanen, 2013).

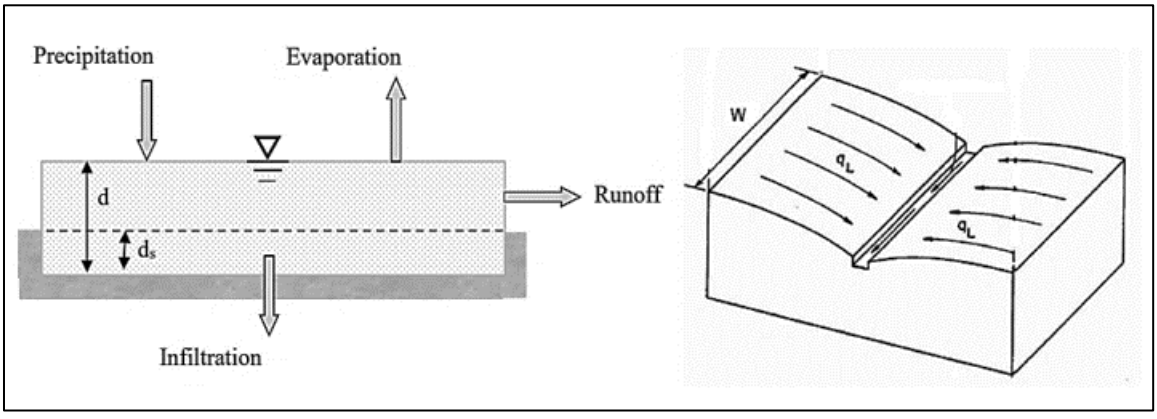


Figure 3-13) propose a nonlinear reservoir model to describe a sub-catchment (Rossman, 2010)

SWMM employs a nonlinear reservoir model to predict surface runoff generated by precipitation inside a sub-catchment, as seen in Figure (3-13).

The sub-catchment is a rectangular area characterized by slope (S) and width (W) that directs drainage to a singular outflow canal. Overland flow is generated by modelling the sub-catchment as a nonlinear reservoir, incorporating precipitation inflow, evaporation, and infiltration losses. The net surplus accumulates to a depth of (d), with the water above this depression storage depth (d_s) generating runoff outflow (q). Initial rainfall abstractions, including surface ponding, interception by flat roofs and vegetation, and surface infiltration, are considered through depression storage. The disparity between input and outflow rates across the subcatchment dictates the net variation in depth per unit of time ($\partial d/\partial t$). (Rossman and Huber, 2016a, Kiraz, 2018).

The principle of mass conservation is:

$$\frac{\partial d}{\partial t} = i - e - f - q \qquad \text{……..(3.4)}$$

Where :

i: Rate of rainfall (m/s)

e: the rate of surface evaporation (m/s)

f: infiltration rate (m/s)

q: Runoff rate per unit of surface area (m/s)

The fluxes i, e, f, and q are all stated in flow rates per unit area (cms/m2 = m/s).

In the metric system (SI), the Manning equation represents the volumetric flow rate Q (cms) of the discharge as uniform flow and slope (S) in a rectangular channel with a width (W) and height (d–ds):

$$Q = \frac{1}{n} S^{1/2} {R_x}^{2/3} A_x = \frac{1}{n} W S^{1/2} (d - d_s)^{5/3} \qquad \text{…... (3.5)}$$

Where:

Q : flow rate Q (cms) = $q \times A$

n : surface roughness coefficient

S : the apparent or average slope of the sub catchment (m/m)

R_x : the hydraulic radius associated with this area (m) = $d - d_s$

A_x: the area across the sub catchment width through which the runoff flows (m^2) = $W(d - d_s)$

By solving the two equations 3.4 and 3.5, it gets:

$$\frac{\partial d}{\partial t} = i - e - f - \alpha\,(d - d_s)^{5/3}\ \alpha = \frac{W\,S^{1/2}}{A\,n}$$

Equation 3.17 is a nonlinear differential equation that can be solved numerically for ponded depth (d) when (d) is greater than (d_s).

When $d \leq d_s$, runoff (q) is zero, and the mass balance on d becomes simple:

$$\frac{\partial d}{\partial t} = i - e - f \qquad \text{..... (3.6)}$$

3.5 The Modeling of Hydraulic Data

3.5.1 Pipe characteristics

To determine the direction of fluid flow and calculate the slope, it is necessary to know the elevations and geographical distribution of the pipes within the model. The drainage system consists of cylindrical pipes with diameters ranging from 315 to 800 mm with lengths extending from 16 to 117 meters. values of the Manning roughness coefficient for pipelines composed of polyvinyl chloride pipes (PVC) are shown in Table (3-5) According to (Bizier, 2007) , the Manning value for PVC pipes is 0.009.

SWMM uses the Manning equation to represent the correlation between flow rate (Q), cross-sectional area (A), hydraulic radius (R), and slope in all conduits (S). For U.S. units:

$$Q = \frac{1}{n} A R^{2/3} S^{1/2} \qquad \text{….. (3.7)}$$

Where:

n: The roughness coefficient measured by Manning for the pipelines (illustrated in Table 3-5)

S: The conduit slope or the friction slope, depending on the flow routing method used.

Table 3-5 The roughness coefficient measured by Manning for the pipelines (Bizier, 2007)

Material conduit	Manning n
Closed Conduits	
Asbestos-cement pipe	0.11 – 0.015
Brick	0.13 – 0.017
Cast iron pipe	
Cement and seal-coated	0.011– 0.015
Concrete (monolithic)	
Smooth forms	0.012 – 0.014
Rough forms	0.015 – 0.017
Concrete pipe	0.011 – 0.015
Corrugated Metal Pipe 1⁄2 in. (13 mm) × $2^{2/3}$ in. (68 mm) Corrugations	
Plain	
Paved invert	0.022 – 0.026
Spun asphalt	0.018 – 0.022
Plastic Pipe (Smooth)	0.011 – 0.015
Polyethylene	0.011 – 0.015
Polyvinyl Chloride	0.009
Vitrified Clay Pipe	0.010
Vitrified Clay Liner Plates	0.011 – 0.015

	0.011 – 0.020
Open Channels—lined	
Asphalt	0.013 – 0.017
Brick	0.012 – 0.018
Concrete	0.011 – 0.020

Data concerning the pipelines was furnished by the administrators of sewerage in Karbala [KSD],2015, Karbala, Iraq, and illustrated in Figure (3-14) below.

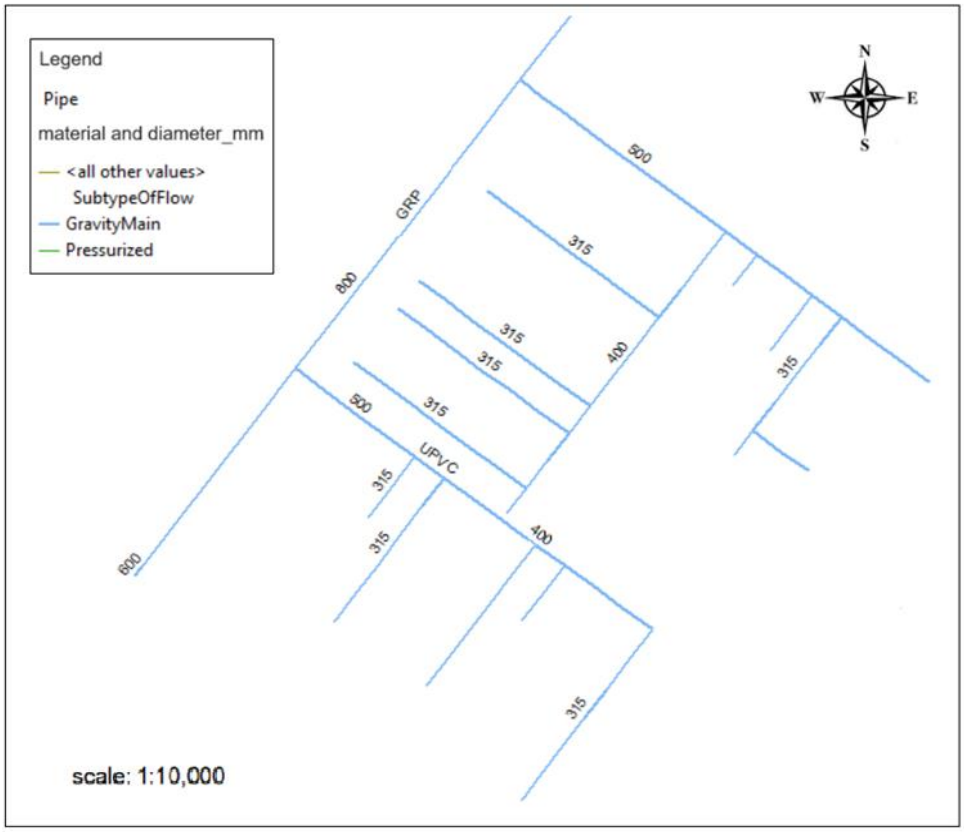
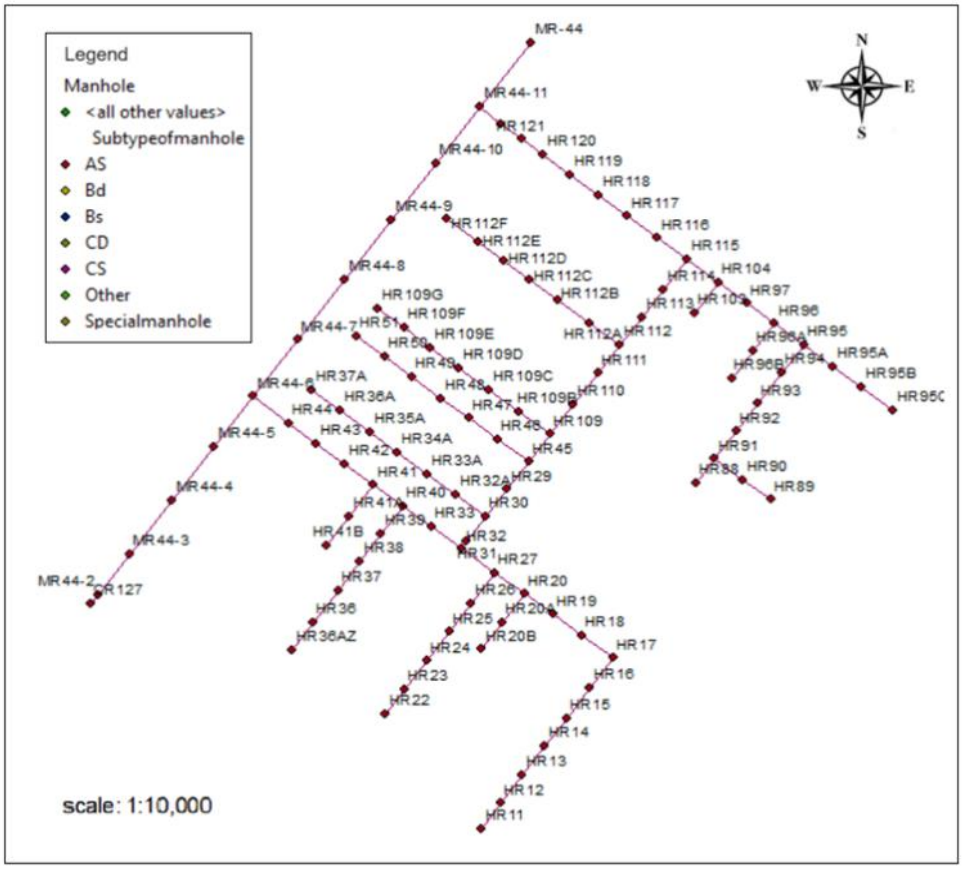


Figure 3-14 Characteristics of pipes in the rainwater network in the Al-Wafaa Quarters.

3.5.2 Manholes

Additionally, manholes are components of the sewer system that facilitate inspection and maintenance. Over time, the materials employed in the construction of manholes have been enhanced. Many enhancements were implemented regarding the materials utilized in manholes. One improvement is the use of precast concrete (Abbas et al., 2019). The system flow rate and flooding are affected by the characteristics of the manholes, including location, type, maximum depth, pressure surge, reflection height, collected area, and external source flow (If found). Determining these characteristics is essential for achieving greater accuracy in simulations. For example, both maximum depth and pressure surge affect the efficiency of manholes in



modeling SWMM.

Figure 3-15 Characteristics of manholes in the rainwater network in Al-Wafaa Quarter's

The rainwater network in the study location comprises 102 manholes, as shown in Figure 3-15, which are classified as CD, Bd, Bs, CS, and AS. The dimensions of the manholes are (60cm * 60cm),(55cm), (35cm * 50cm), and (60cm * 90cm). In table (3-6) below, the manhole properties of the study area from the Directorate Kerbala Sewage [DSK, 2023] are illustrated.

Table 3-6 Stormwater Systems in the Study Area: Manhole Properties [DSK, 2023]

Manholes Information	Stormwater system
Number of manholes	339
Manholes subtypes	CD, Bd, Bs, CS, AS
Manholes Wall material	Concrete
Ground elevation range (m)	32.876 − 39.430
Invert elevation range (m)	28.230 – 37.259
Maximum depth range (m)	1.191 – 8.185
Access diameter (cm)	35×50, 55, 60×60, 60×90

3.5.3 Pump station

The Al-Wafaa district's terrain is nearly flat, necessitating the installation of pumping stations in specific regions of the network system to facilitate the movement of rainwater through the network. Pumps are devices that elevate the hydraulic head of water to greater heights. In the studied area, pumping stations are essential to ensure that rainwater is efficiently transported through the sewers and discharged at the discharge point. Water

is exclusively supplied to the pumping station in the Al-Wafaa district for the study area. The station is equipped with three submersible pumps and an 800 mm-diameter inlet conduit.

3.6 Analysis of Sensitivity

Sensitivity analysis is a critical step in the parameter recognition procedure. This process identified the most sensitive parameters of the model, allowing for their calibration (van der Sterren et al., 2014). A variety of coefficients have been employed as calibration parameters (Rezaei et al., 2019, Li et al., 2016). There are two categories of sensitivity analyses: local and global. Sensitivity analysis was performed in this study using a modified Morris screening methodology. The Morris screening approach also provides a cumulative calculation of the sensitivity of curvature and factor correlations, as well as a sensitivity estimate of the full effect of a given factor on performance (Campolongo and Braddock, 1999). The following formula:

$$S_{i,j} = \left| \sum_{i=1}^{n} \frac{(Y_{i+1} - Y_i)/Y_i}{(P_{i+1} - P_i)/P_i} / n \right| \qquad \ldots. \ (3\text{-}8)$$

where Si, j is the parameter's sensitivity, Yi represents the variable output of the i-th model run, Yi+1 represents the variable output of the i+1-th model run, and the parameter's change in relation to the beginning value.

In the i-th model run, the parameter is represented by Pi, the parameter's change in relation to the initial parameter for the i+1-th model run is represented by Pi+1, and the number of model runs is represented by n. the impact of specific parameters on the output of a variable in a simulated

1) Insignificant: Si,j < 0.25;

2) Influential: $0.25 \leq S_{i,j} < 1$;

3) Very influential: $1 \leq S_{i,j} < 2$; and

(4) Extremely influential: $S_{i,j} >= 2$. The parameters need to be modified in general when Si, j exceed 0.25.

In this investigation, model calibration was performed manually through trial and error, adjusting sub-catchment properties to minimize the discrepancy between measured and modeled discharges. It is an important method for understanding the impact of different operational factors on a stormwater network; among these important parameters are the sub-catchment width, Manning's roughness coefficient, and the impervious percent factor.

3.7 Calibration and validation

The performance of the model was compared with the system intended to be verified in this study, where the model was calibrated by comparing the actually measured discharge in the Al-Wafa neighborhood, using the Manning equation, with the expected discharge in the pipes extracted from the SWMM program. Model validation includes the correlation coefficient (R) and the Normalized Mean Square Error (NMSE). The NMSE is calculated to estimate the average relative dispersion that considers both systematic and random errors. The determination coefficient (R^2) is a calculation that specifies the intensity and direction of the relationship between two variables. It is occasionally referred to as the linear correlation coefficient. R (equation 3.10) represents the linear relationship between the variables and is, therefore, insensitive to any additional or multiplier factor. In contrast, the NMSE equation (3.9) measures the average relative dispersion and reflects systematic and random errors.

$$NMSE = \frac{\overline{(C_o - \overline{C_p})^2}}{\overline{C_o C_p}} \quad \text{……(3.9)}$$

$$\mathbf{R} = \frac{\overline{(C_O - \overline{C_O})(C_P - \overline{C_P})}}{\sigma_{C_O}\sigma_{C_P}} \quad \text{…… (3.10)}$$

Where:

Co = designed volume flow rate

Cp = simulation of volume flow rate

¯Co = average designed flow rate

¯Cp = average of simulated flow rate

σ C = standard deviation.

The acceptable limits for these statistical criteria are $1 \geq R > 0.8$ and $0 \leq RMSE < 1.5$.

3.8 Low-impact development simulation

Surface discharge is absorbed and treated through detention, infiltration, and evapotranspiration in low-impact development, or LID. Subcatchment properties are regarded in the same manner as aquifers and snowpacks (Rossman, 2010).

The SWMM can explicitly model the following categories of the GIs as some examples of (LID) controls:

1. Bioretention Cells: depressions above the gravel drainage bed are used to retain vegetation cultivated in a combination of engineered soils. The water is stored, infiltrated, and evaporated, including direct rainfall and runoff from adjacent areas.

2. Rain Gardens are specialized forms of bio-retention cells entirely composed of artificial permeable soil and lacking a gravel substrate.

3. "Green Roofs": A soil layer located at the roof's summit that facilitates the removal of excess percolated rainfall.

4. Infiltration Trenches they are narrow channels filled with gravel, gathering rain water from non -permeable areas. Provides an additional storage capacity and time to enable the collected water to leak to the original soil below .

5. Continuous Permeable Pavement: Excavated areas are filled with gravel and covered with a porous concrete or asphalt mixture. Block paver systems consist of impervious paver blocks on a sand or pea gravel substrate with a gravel storage layer beneath.

6. Cisterns (or rain barrels): These containers collect rainwater that falls from roofs during storms and reuse or drain it during dry periods.

7. Rooftop Disconnection: Instead of using drainage channels, the downpipes are directed to areas covered with plants or green spaces. Roofs can also be designed to be directly connected to the sewer, which causes water to overflow into the previous areas.

8 Vegetative Swales are depressions or channels with sloping sides covered with grass and other plants. They delay the collected water flow, allowing it time to seep into the original soil beneath.

The following procedures were implemented for the design of LID :

1. As shown in Figure (3-16), LID was allocated to each sub-region, and the flow of rainwater was transferred to it in MR-44 using the control editor in LID .The Rain Garden was chosen as a Low Impact Design (LID) measure. In this study, rain gardens integrate landscaping with stormwater management. Plants can absorb rainwater, dissipate it into the atmosphere, or infiltrate it into groundwater through green infrastructure, which improves water quality. The main goal of these gardens is to restore evaporation and natural absorption of water on-site, in addition to providing green spaces in cities. Rain gardens can provide environmental, social, and economic

advantages. They can be installed at street intersections and sidewalk corners (Alyaseri et al., 2021).

Rain garden consist of a low-lying area containing plants, a mixture of manufactured soil, and a drainage bed of sand or gravel that meets water reuse requirements. The educational structure includes multiple layers to enhance absorption and support plant growth (Rossman, 2010).

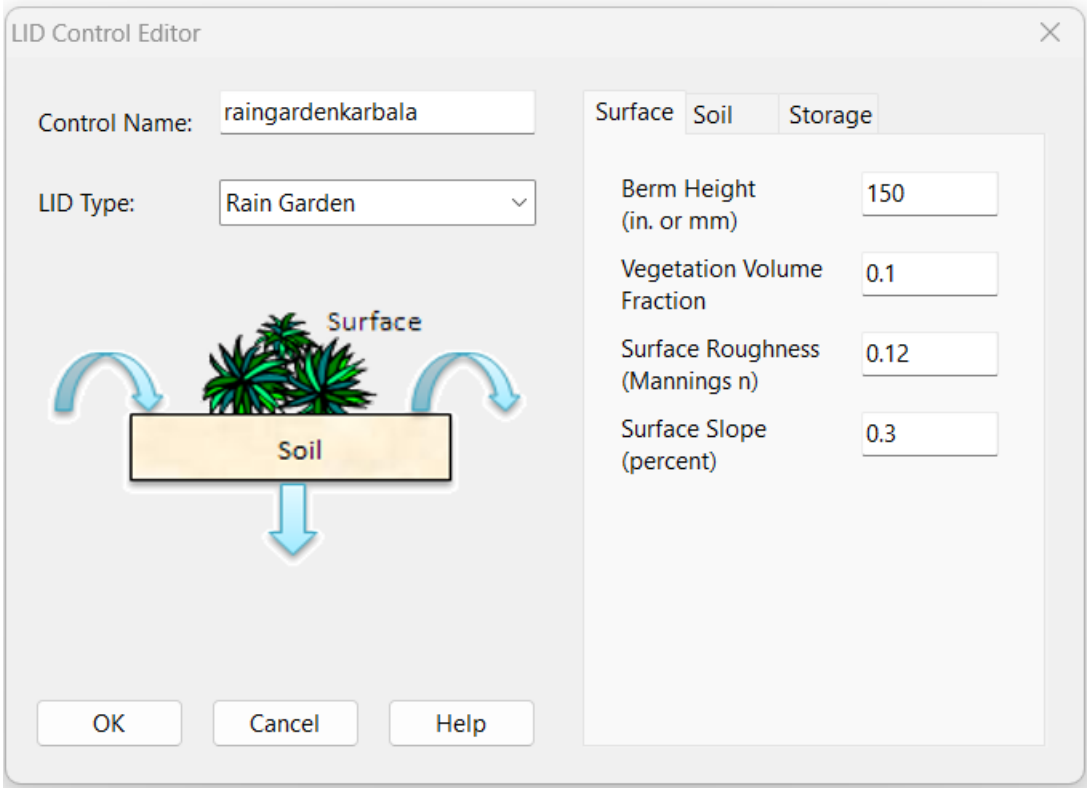


Figure 3-16 LID of the editor.

2. The configuration characteristics of this study's rain garden are equally important input criteria, as illustrated in Table (3-7), as specified in the SWMM user's manual (Rossman, 2010) and (Zhang et al., 2020).

Table 3-7 Parameters of partial .permeability of LID (Bai et al., 2018)

Layer	Parameter	Unit	Green Roof	Rain Garden	Bio-Retention Cell
Surface	Berm Height	mm	50	150	150
	Vegetation Volume Fraction	-	0.2	0.1	0.05
	Surface's roughness	-	0.13	0.12	0.12
	Surface Slope	percent	1	0.3	0.1
Pavement	Thickness	mm	-	-	-
	Void radio	-	-	-	-
	Permeability	mm/hr.	-	-	-
Soil	Thickness	mm	200	500	500
	Porosity	-	0.5	0.3	0.5
	Field capacity	-	0.3	0.2	0.2
	Wilting point	-	0.1	0.1	0.07
	Conductivity	mm/hr.	700	500	110
Drainage mat	Thickness	mm	100	-	-
	Void fraction	-	0.43	-	-
	Roughness	-	0.03	-	-
Storage	Thickness	mm	-	-	260
	Void radio	-	-	-	0.75
	Seepage rate	mm/hr.	-	200	80
Drain	Flow coefficient	-	-	-	0
	Flow exponent	-	-	-	0.5

	offset height	mm	-	-	150
Surface	Berm Height	mm	25	150	200
	Vegetation Volume Fraction	-	0	0	0.1
	Surface's roughness	-	0.12	0.24	0.13
	Surface Slope	Percent	1	1	0.8
Pavement	Thickness	mm	60	-	-
	Void radio	-	0.13	-	-
	Permeability	mm/hr.	200	-	-
Soil	Thickness	mm	150	-	-
	Porosity	-	0.5	-	-
	Field capacity	-	0.1	-	-
	Wilting point	-	0.024	-	-
	Conductivity	mm/hr.	100	-	-
Drainage mat	Thickness	mm	-	-	-
	Void fraction	-	-	-	-
	Roughness	-	-	-	-
Storage	Thickness	mm	250	600	-
	Void radio		0.43	0.75	-
	Seepage rate	mm/hr.	600	24	-
Drain	Flow coefficient	-	0.69	0.69	-
	Flow exponent	-	0.5	0.5	-
	offset height	mm	6	6	-

3. As shown in Figure (3-17), LID technology can be integrated for each sub-catchment. The sub-drainage basin represents 39 typical sub-drainage basins within the research area, as shown in Figure (3-18). The selected LID system includes 7% of the area of each sub-drainage basin, while 40% of the

impervious land in each sub-drainage basin is managed by a designated rain garden, shown in Figure (3-19).

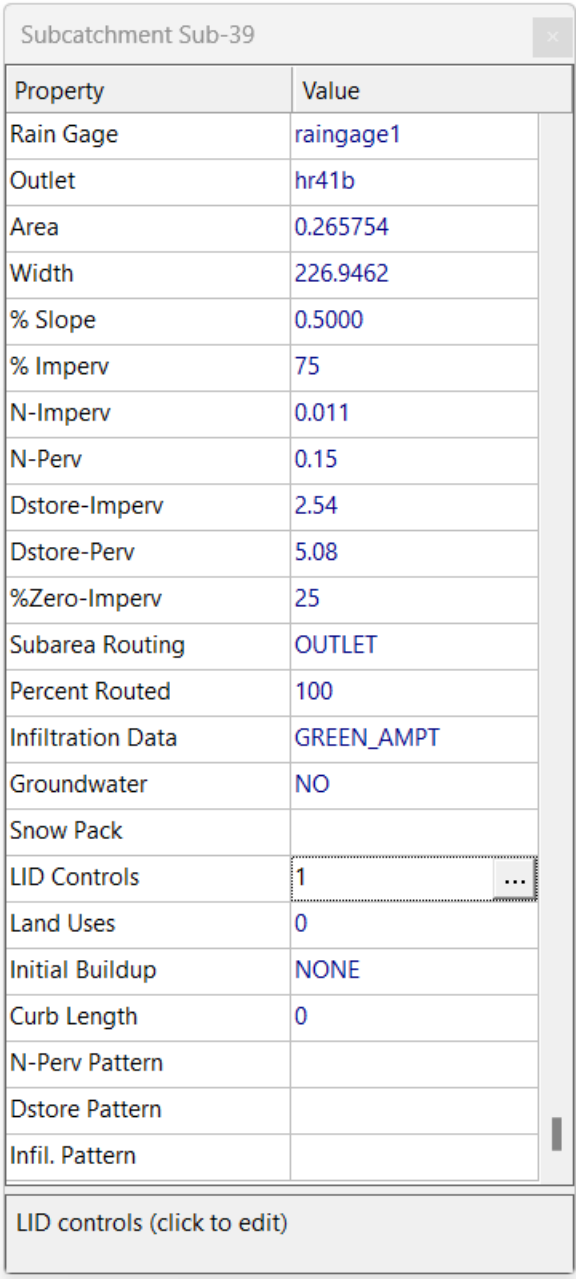


Figure 3-17 Features of the sub-catchment with the number(39).

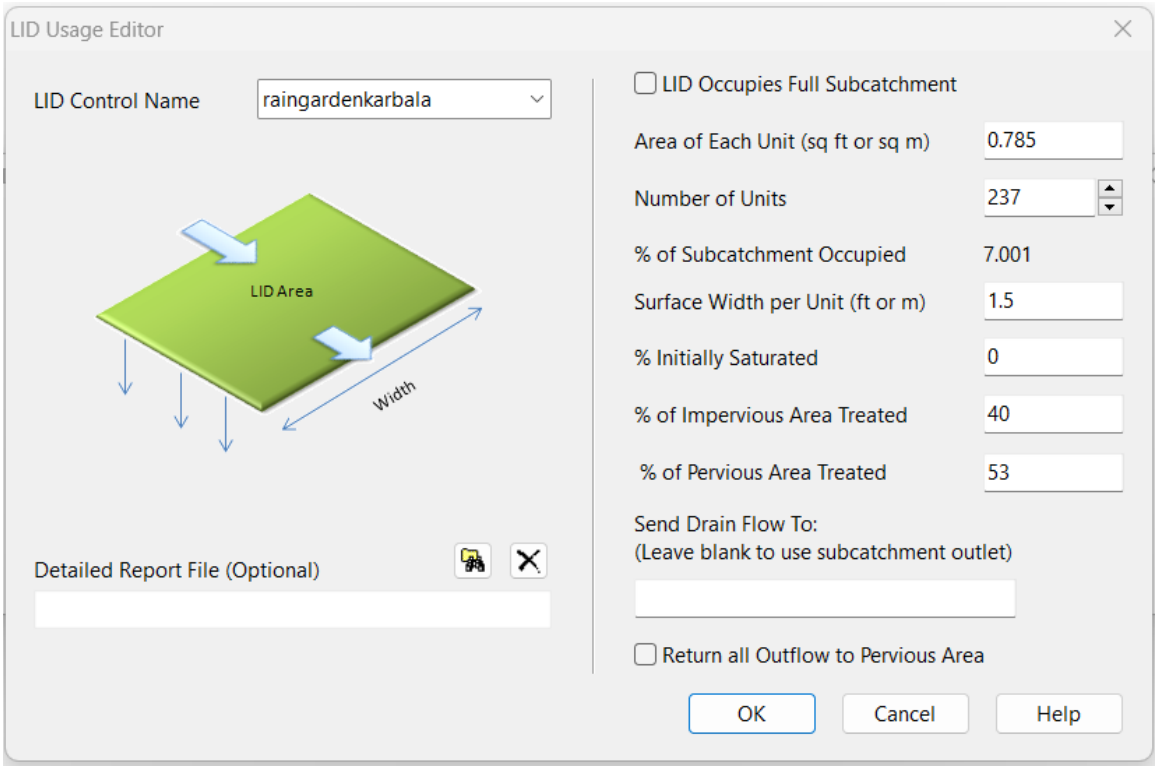


Figure 3-18 For sub-catchment number 39, the LID usage editor is applicable.

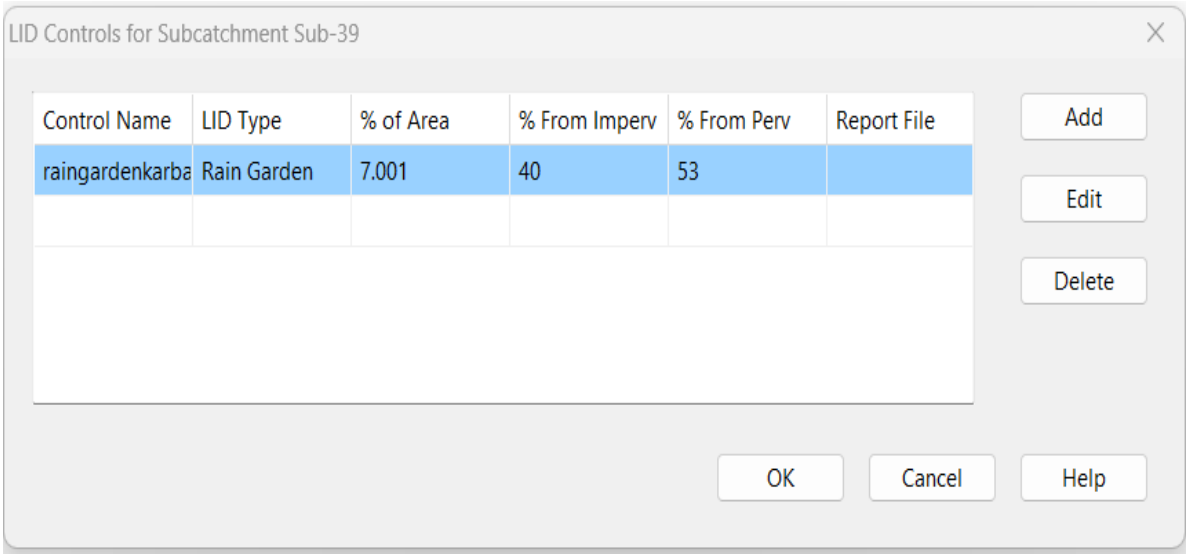


Figure 3-19 includes LID controls within sub-catchment number 39.

Chapter Four: Results and Discussion

4.1 Introduction

The (SWMM) program was employed to obtain the analysis results in this chapter, which were evaluated for the rainwater network system during rainfall in the Al-Wafa neighborhood and provide appropriate scenarios in the following :

1- Draining rainwater during rainy weather and with a design rainfall intensity of 12 mm/hr.

2- Draining rainwater during rainy weather and with different rainfall intensities for return periods of 2,5,10,20 years.

3- Providing a solution to mitigate flood incidents through:

I. Applying one of the LID methodologies.

II. Installing three additional pipelines for the network.

The chapter presents the results obtained using statistical and physical models, where the results of SWMM modeling will be displayed. These results were analyzed to achieve the objectives explained in the first chapter,

4.2 Rainfall intensity modeling

Statistical analysis was used to estimate rainfall intensity over different periods and multiple return periods, using frequency analysis techniques to evaluate rainfall patterns during rainy weather conditions.

4.2.1 Generating IDF Curves

Intensity-duration-frequency (IDF) profiles were established and generated by frequency analysis using the Gumbel distribution. The average daily

rainfall length was determined based on daily precipitation data recorded throughout the year, including the maximum daily rainfall over 40 years (1984-2024). Table (4-1) shows the probability of rainfall intensity at different return intervals (2,5,10, and 20 years) and at time intervals of 5 minutes.

The rainfall duration range was set between 5 and 120 minutes with 5-minute intervals, and rainfall intensity was calculated using the Sherman equation(3-1) for return periods of 2, 5, 10, and 20 years. The results of these calculations are shown in Table (4-1).

IDF curves were created to illustrate the relationship between intensity and time using the Gumbel distribution, based on the calculated values listed in Tables (4-1) and (4-2) for the specified return periods, covering the time periods from 5 to 120 minutes with time intervals of 5 minutes, as shown in Figure (4-1).

The mathematical model extracted for the IDF curves allows for rapid estimation of rainfall intensity for any period and any required return period. The calculation was performed using the mm/hr unit, focusing on periods less than 24 hours.

The results of the Gumbel distribution showed that the calculated rainfall intensity was the highest when compared to other statistical distributions, which contradicts the conclusions of (Koutsoyiannis, 2003) who indicated that the Gumbel (EV1) distribution gives the lowest values for rainfall intensity compared to other distributions. However, these results are consistent with the studies of (Elsebaie, 2012) and (Rasel and Islam, 2015) Those studies demonstrated that the Gumbel distribution produces the

highest estimates of rainfall intensity when analyzing annual rainfall data in the research areas.

The values extracted from the Gumbel distribution were used in the analysis of temporal data within the SWMM model to simulate the performance of the rainwater drainage system, which contributed to providing more accurate estimates of the probability of flooding

Table 4-1 The intensity of rainfall for four return periods.

Storm Duration (min)	Storm frequency in years				Storm Duration (min)	Storm frequency in years			
	2	5	10	20		2	5	10	20
5	40.5	60.4	60.4	60.4	65	9.2	13.7	16.7	19.5
10	27.1	73.6	73.6	73.6	70	8.8	13.1	16.0	18.7
15	21.4	86.3	86.3	86.3	75	8.4	12.6	15.3	18.0
20	18.2	40.4	40.4	40.4	80	8.1	12.1	14.8	17.3
25	16.0	49.3	49.3	49.3	85	7.9	11.7	14.3	16.7
30	14.4	57.7	57.7	57.7	90	7.6	11.3	13.8	16.2
35	12.9	32.0	32.0	32.0	95	7.4	11.0	13.4	15.7
40	12.1	39.0	39.0	39.0	100	7.1	10.7	13.0	15.2
45	11.2	45.6	45.6	45.6	105	6.9	10.4	12.6	14.8
50	10.7	27.1	27.1	27.1	110	6.8	10.1	12.3	14.4
55	10.0	33.0	33.0	33.0	115	6.6	9.8	12.0	14.0
60	9.6	38.6	38.6	38.6	120	6.4	9.6	11.7	13.7

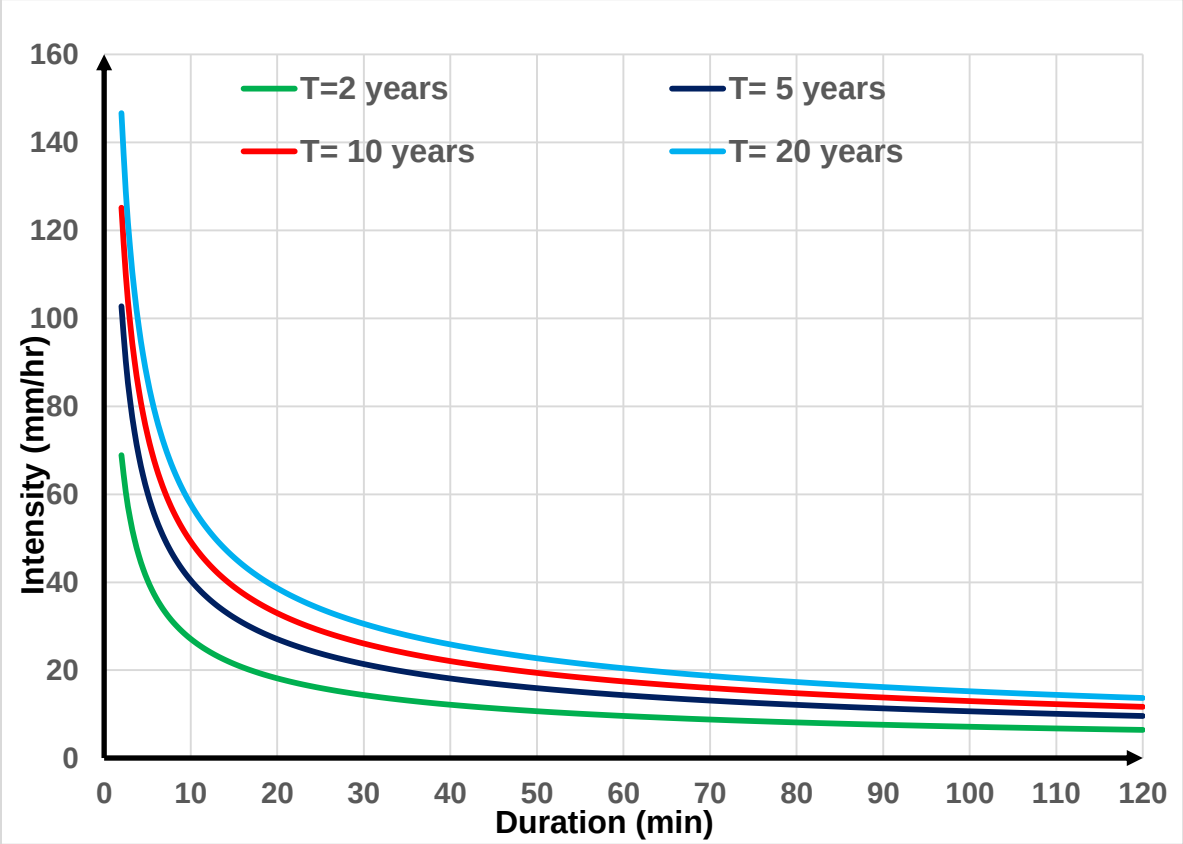
Table 4-2 The intensity of rainfall (mm/hr) at different frequencies

Rainfall intensity mm/hr.								
Time (min) / Return period(year)	120	100	80	60	40	20	10	5
2	6.4	7.1	8.1	9.6	12.1	18.2	27.1	40.5
5	9.6	10.7	12.1	14.3	18.1	27.1	40.4	60.4
10	11.7	13.0	14.8	17.4	22.1	33.0	49.3	73.6
20	13.7	15.2	17.3	20.4	25.9	38.6	57.7	86.3

Figure 4-1 The Rainfall IDF curve figure illustrates a diagram derived from statistical data used to determine rainstorm intensity in Kerbala City, Iraq, for 2, 5, 10, and 20 years of rainstorm frequency.

4.2.2 Selecting rainfall intensity for modelling

In this study, the IDF curve equations were used to accurately estimate rainfall intensity for any time period and any return period. Rainfall intensity was calculated in mm/hr units for a set of return periods with an emphasis on periods less than 24 hours, where the rainfall duration used ranged between 5 and 120 minutes with time intervals of 5 minutes for return periods of 2,5,10,20 years. The results of the Gumbel distribution showed that rainfall



intensity was higher compared to other statistical distributions. These values were used in the analysis of time data using the SWMM model to simulate

the performance of the drainage system, which helped provide more accurate estimates of the probability of flooding limits. Model calibration and validation

The validity of the stormwater drainage system modelling in the Al-Wafaa neighbourhood main rain (MR-44) was verified by comparing the drainage data designed by the Karbala Sewerage Directorate with the expected data from the model SWMM. The current study relied on analyzing the relationship between the results using the mean square error (NMSE) and the coefficient of determination (R^2). The performance of the SWMM modelling was evaluated by comparing the design flow rates with the values extracted from the model for 102 pipes using the (NMSE) and (R^2) indicators. The statistical results of these relationships at different return periods are presented in Table (4-3), while Figures (4-2) to (4-5) show the comparison between the expected and designed data.

Table 4-3 Calibration of SWMM data with design data.

The Parameters	Normalized Mean Square Error (NMSE)	determination coefficient (R^2)
Perfect fit	0	1
Validation limits / Recurrence Interval (years)	≤1.5	>0.8
2	1.16	0.9342

5	0.998	0.9707
10	0.97	0.9572
20	0.93	0.8999

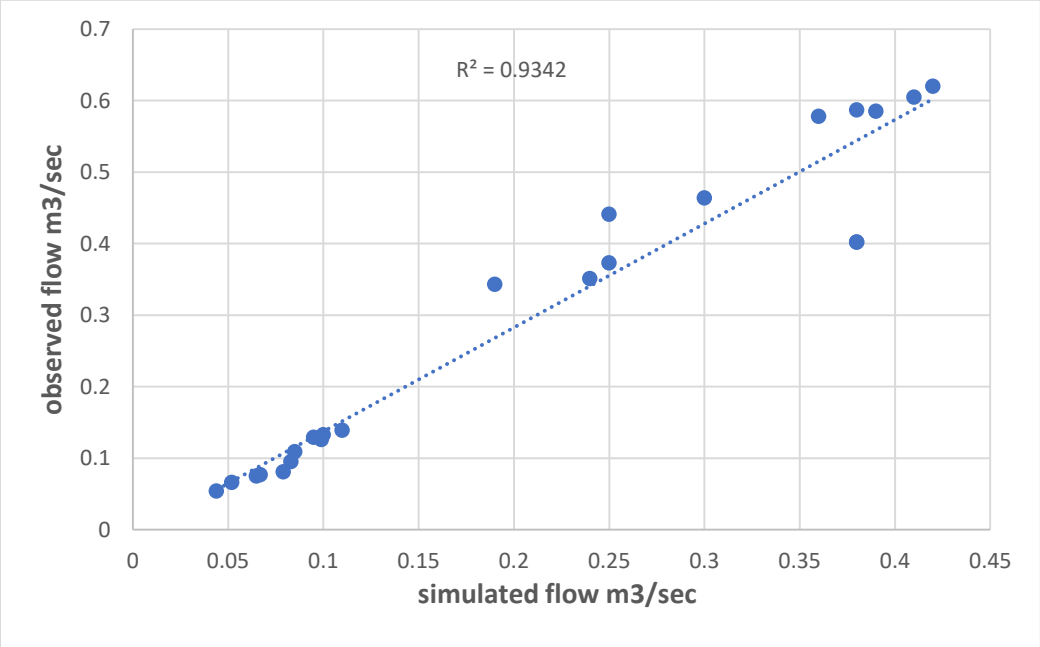


Figure 4-2 Using data from 2 years of rainfall, density, and return periods, the SWMM model calculates the coefficient of determination (R^2) between the design and maximal discharge.

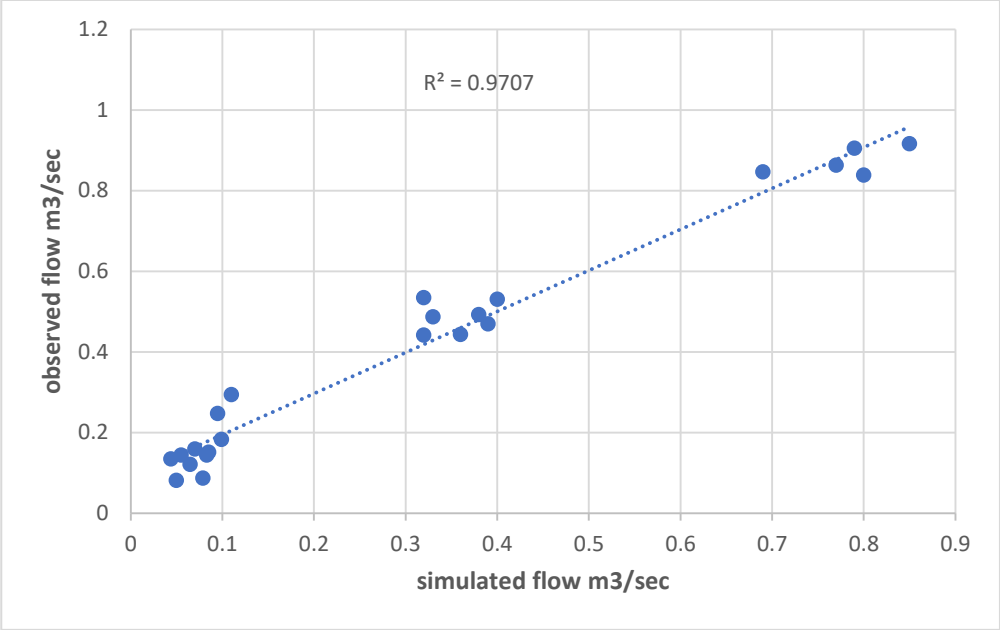


Figure 4-3 Using data from 5 years of rainfall, density, and return periods, the SWMM model calculates the coefficient of determination (R^2) between the design and maximal discharge.

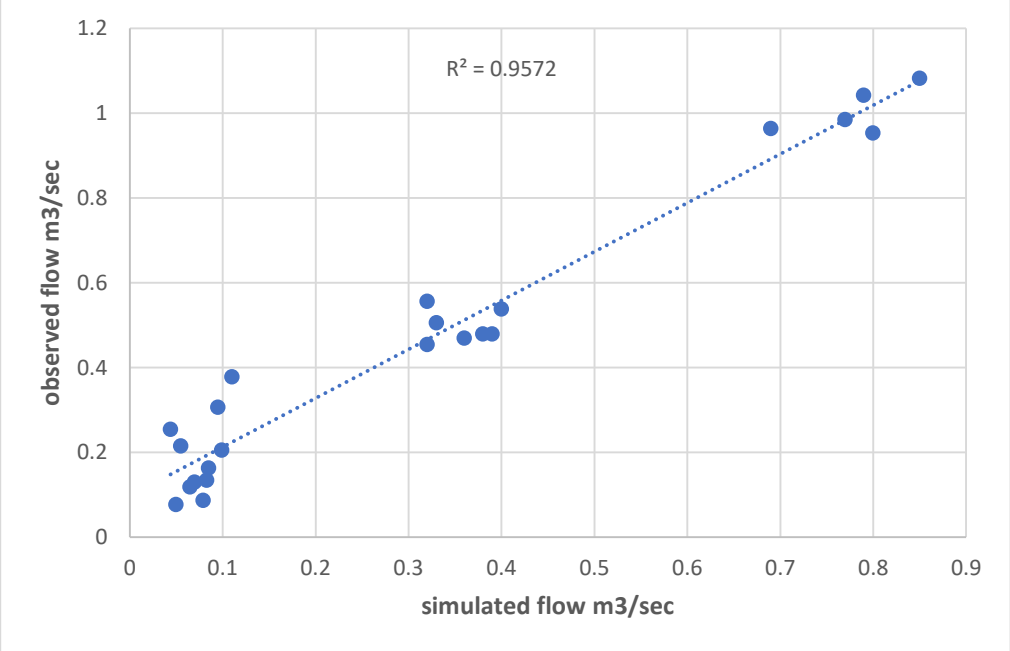


Figure 4-4 Using data from 10 years of rainfall, density, and return

periods, the SWMM model calculates the coefficient of determination (R^2) between the design and maximal discharge.

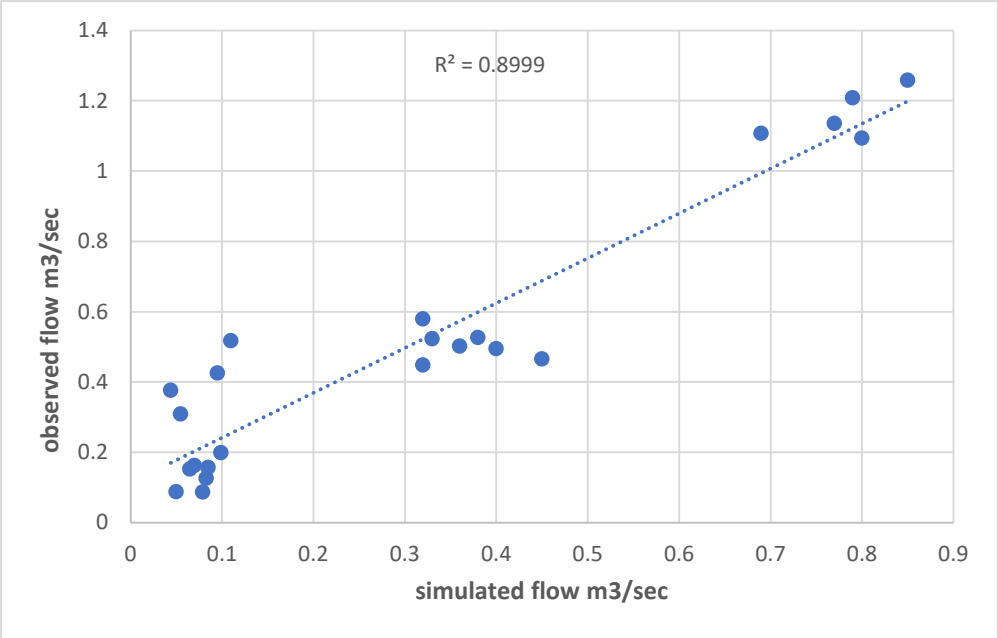


Figure 4-5 Using data from 20 years of rainfall, density, and return periods, the SWMM model calculates the coefficient of determination (R^2) between the design and maximal discharge.

Table (4-3) and Figures (4-2) to (4-5) the values extracted from the used indicators show a convergence at the beginning of the simulation time, reflecting the low flow rates in the pipes when the stormwater network starts operating. In contrast, the high values reflect higher flow rates in the pipes located at the end of the system, where the flow increases gradually. due to flow accumulation and increasing pipe diameters.

The value of R^2 in Figure (4-2) for the two-year return period (0.934) was close to (1), which means that the designed discharge and the expected behavior in the program were close values, and the values of the Normal Square Mean Error (NMSE) were equal to 1.16 while Figure (4-3) shows that in the five-year return period the value of R^2 increased and became

(0.97), which is the highest value among the return periods it is considered the best performing model of SWMM. The value of the Normal Square Mean Error (NMSE) was equal to 0.998.

As in figure (4-4), the values of determination coefficient R^2 (0.957) were achieved in the return period of ten years, and the value NMSE was equal to 0.97, while the value of R^2 in the return period of 20 years was 0.899 as shown in the figure (4-5). The value of NMSE was equal to 0.93.

Rainfall intensity was studied for different return periods to calculate the range of mean square error values (NMSE) between (0.93 and 1.16). It was found that the model for the family period is 20 years, as shown in Figure (4-5), achieved the lowest value for NMSE, which indicates the best performance of the model. The value of R^2 ranged between 0.934 and 0.899, while the value of R^2 in the return period of 5 years was higher because its return period is short, which makes it easy to predict. The error rate increases R^2 the longer the prediction period of the event.

The results showed that the value of NMSE was very close to zero, indicating a high fit. The value of the coefficient of determination R^2 also showed a positive correlation. It was close to the ideal value 1, confirming the existence of a strong linear relationship and a high agreement between the expected and designed data. This indicates the ability of the SWMM model to predict data with high accuracy. The results showed that the model-generated maximum flows are close to the designed maximum flows.

4.3 Climate change's impact on the rainwater drainage system

SWMM simulation was used to evaluate the drainage system of the Al-Wafa neighbourhood before and after rainwater infiltration, as the surface runoff volumes on the sub-watersheds due to rainfall reached when levels become higher than the design capacity of the network system, flooding may occur in the drainage system nodes, which was observed to varying degrees within the stormwater network in the research area under different rainfall intensities during different return periods. Figure (4-6) shows the drainage network system at a rainfall intensity of 12 mm/hr, which is the design intensity of the selected network, where the network was evaluated during this intensity. The simulation showed that the rainwater network was not exposed to any flooding. The results showed that the system operates efficiently at the design density, while the area experiences flooding during periods of heavy rainfall that exceed the designed rainfall density. An assessment of the impact of climate change on the differences in rainfall intensity in the study area was conducted because climate change is associated with increased drainage in the area. Increased rainfall intensity in urban areas in general (Ogunrinde et al., 2020).

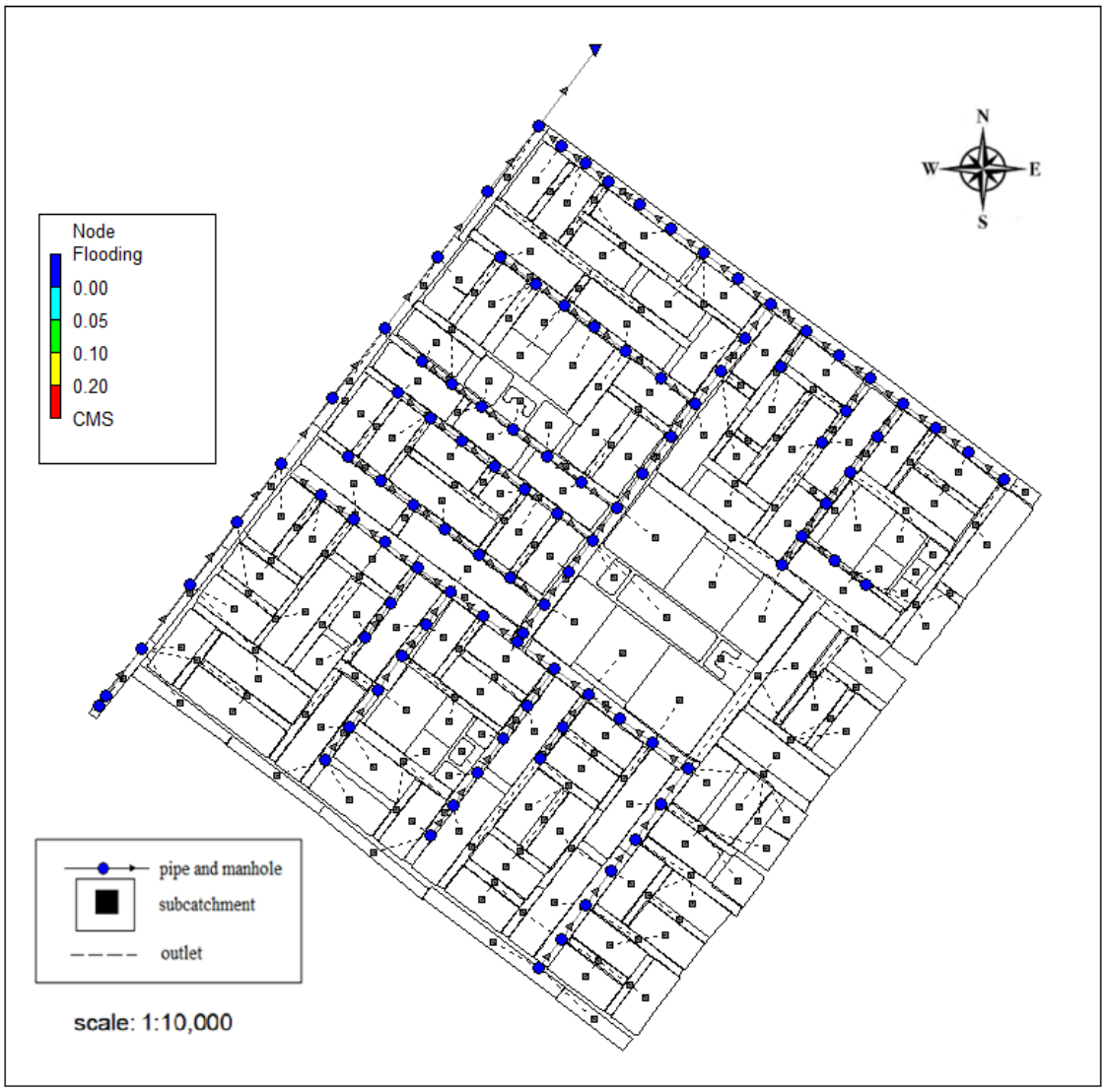


Figure 4-6 Assessment of the Al-Wafaa Quarter rainwater network before stormwater leaking.

4.3.1 The quantity of stormwater that flows untreated during damp weather

The rainwater network in the Al-Wafaa district was analyzed after rainfall at different return periods of 2,5,10, and 20 years, where the impact of rain on the network performance was evaluated due to the increased intensity of rainfall and, consequently, the increased amount of water entering the network.

The table (4-4) generated using the SWMM simulation shows the total flood volume, the number of flooded manholes, the maximum network flow rate (sum of flows in all pipes) for return periods of 2,5,10,20 years, and the duration of a 2-hour rainfall event.

Rainfall intensity increases with return periods due to climate (Ogunrinde et al., 2020), leading to increased water leakage into the system. The table shows the total flood volume, maximum flow rate, and number of flooded manholes analyzed during the event. For example, the maximum flow rate during a two-year return period was 1.079 m^3/sec with a total flood volume of 6921 m^3 with 31 manholes flooded, equivalent to 30% of the total manholes. At a five-year return period, the maximum flow rate increased to 1.453 m3/sec, the total flood volume reached 8441 m3, and the number of manholes flooded increased to 38 manholes. At a 10-year return period, the maximum flow rate was 1.669 m3/sec, and the flood volume increased to 9247 m^3/sec while the number of manholes flooded increased to 42 manholes. At a 20-year return period, the maximum flow rate was 1.927 m3/sec, and the total flood volume reached 9956 m^3 with the number of manholes flooded increasing to 48 manholes, indicating that longer time periods increase flood intensity. (47 % of total flooded manholes). The study

of (Wen et al., 2013) showed a positive relationship between the return period of rain and the flooding of stormwater drainage networks.

Table 4-4 Impact of precipitation occurrences on Al-Wafaa Quarter MR-44

Return period duration (per year)	During Period. (hr.)	Max. flow (m^3/s)	Total flood Volume. (m^3)	No.flooded manhole
2	2	1.079	6921	31
5	2	1.453	8441	38
10	2	1.669	9247	42
20	2	1.927	9956	48

During this period, most excess stormwater is anticipated to be discharged through MR-44. Flooding may occur if the volume of water running out of manholes or sewers exceeds the maximum values intended. The sub-catchment regions of Al-Wafaa District are illustrated in Figures (4-7),(4-8),(4-9), and (4-10), which depict the locations, categories, and percentages of flooded manholes. Understanding flood locations is essential for the identification of specific flood issues. As a result, it is expected that this investigation will provide a technical response to decision-makers,

engineers, and specialists, enabling them to identify systemic issues and evaluate potential solutions. As indicated by (Hassan et al., 2017).

Blue dots represent non-flooded nodes, and dots marked with other colours (e.g., cyan, green, yellow, and red) represent flooded nodes with different flood rate values (see legend).

In Table (4-5), the SWMM simulation distinguishes the five phases of flooding from manholes.

Table 4-5 The discharge rate of the excess manholes in the network, according to the SWMM modeling

Stage	Percent of manholes flooding %
1	No flooding from (0 to 0.001 m^3/s)
2	Very mid-flooding (> 0.05m^3/s)
3	Moderate flooding (> 0.1 m^3/s)
4	Extreme flooding (> 0.2 m^3/s)
5	Very hight flooding. (> 0.4 m^3/s)

The table shows different stages of flooding in manholes based on the maximum flow rate. Each stage represents a different degree of flooding. The greater the water flow, the greater the severity of the flooding affecting the manhole.

Stage 1: No Flooding (0 to 0.001 m^3/s) At this stage, there is almost no flooding, or the flow is so low that it is not considered a significant flood. If the water flow in the hole does not exceed 0.001 m^3/s, it does not fill the hole or cause significant water accumulation.

Stage 2: Very light flood(> 0.05m^3/s) At this stage, the flood is light, and the flow is greater than 0.05m^3/s but does not exceed 0.01m^3/s.

Stage 3: Moderate Flood (> 0.1 m^3/s) Floods become more pronounced at this stage as the flow increases to more than 0.01 m3/s, raising the water level in the manhole.

Stage 4: A severe flood (> 0.2 m3/s) occurs when the flow exceeds 0.02 m3/s. This flood leads to a clear accumulation of water in the manhole and thus affects the area surrounding it, such as buildings or roads.

Stage 5: Very High Flood (> 0.4 m^3/s) This stage is considered the most extreme stage of flooding, where the flow exceeds 0.04 m^3/s. With this high flow, major flooding occurs in manholes and surrounding areas, which can cause traffic disruption on roads or affect buildings.

Shows Figure (4-7) the flooding of the rainwater network in the Al-Wafaa neighborhood during the two-year return period, as rainwater flooded a number of manholes in the network, flooding several areas in the neighborhood. The figure shows the locations of the flooded manholes. The figure shows that 30% of the total flooded manholes were flooded by rainwater.

It is noted that stage 1 (no floods) accounted for 69% of the total manholes, while stage 2 (low floods) accounted for 17%. Stage 3 (medium floods) had 8% of the total manholes, while stage 4 (high floods) had 5%. The last stage, which is 5 (very high floods), accounted for only 1% of the total manholes, as the flood continued with increasing rainfall.

Figure (4-8) shows the floods in the network for a five-year return period and shows the locations of the flooded manholes. The figure shows that 37% of the total manholes were flooded with rainwater. It is noted that the first stage (no floods) constituted 63% of the total manholes, while the second stage (low floods) constituted 9%. The third stage (medium floods)

constituted 14% of the total manholes, while the fourth stage (high floods) constituted 12%. The last stage, which is 5 (very high floods), constituted only 2% of the total manholes; this result is consistent with (Hassan et al., 2017), who found that 32% of manholes will be flooded if rainfall increases to 15 mm/hr for 5 return periods.

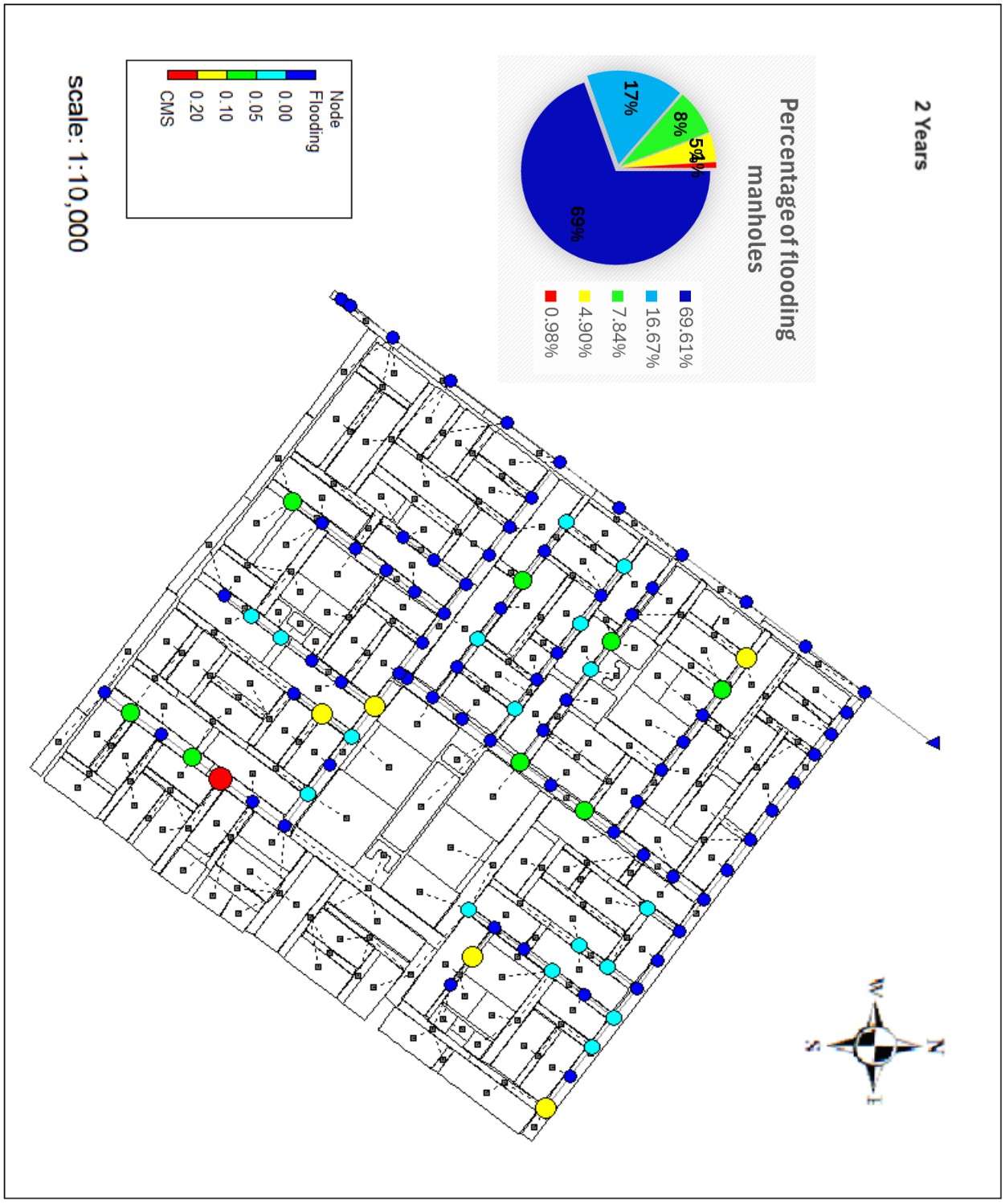


Figure 4-7 Al-Wafaa at a two-year return time, the quarterly assessment of the rainwater network is conducted during stormwater leaks.

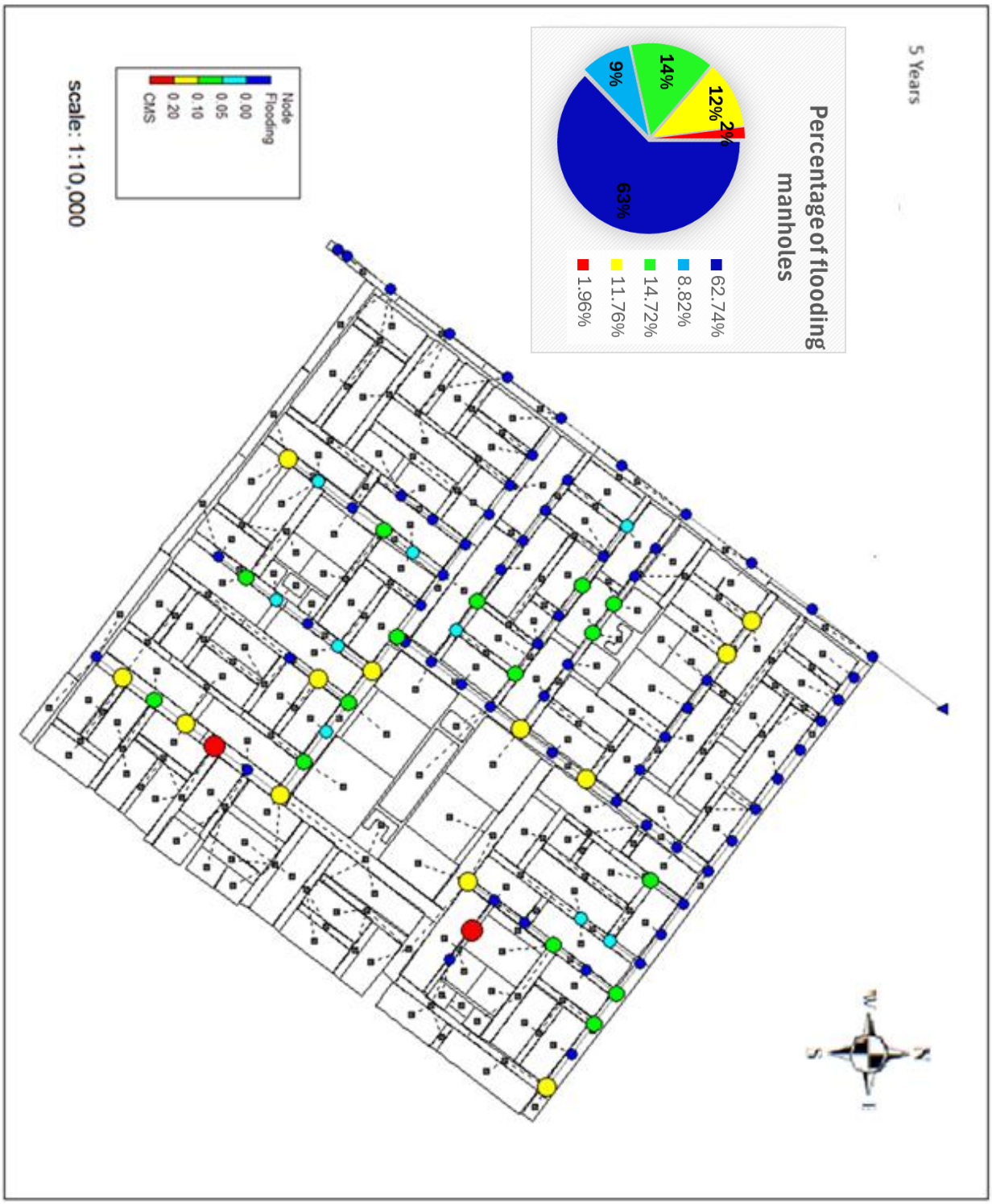


Figure 4-8 Al-Wafaa at a five-year return time, the quarterly assessment of the rainwater network is conducted during stormwater leaks.

Figure (4-9) In the return period of 10 years, it was noted that the manholes that were not flooded in the first stage were 59% of the total manholes, and in the second stage of low floods, the percentage of flooded sewage openings was 8% of the total manholes, and the medium floods in the third stage were 10% of the total manholes, and the high and heavy floods in the fourth stage were 18% of the total manholes, and 5% of the total manholes in the five stages in the case of high and severe floods, where it was noted that during this period (10 years) .

After the return period was changed to 20 years. Figure (4-10) illustrates a substantial increase in the flood, as the first stage was 53% of the total manholes without flooding, while the second stage was 12% of the total manholes. There were very low floods and moderate floods in the third stage, which reached 10% of the total manholes, while the heavy floods in the fourth stage reached 18% of the total manholes, and the fifth is considered severe flooding, which reached 7% of the total manholes.

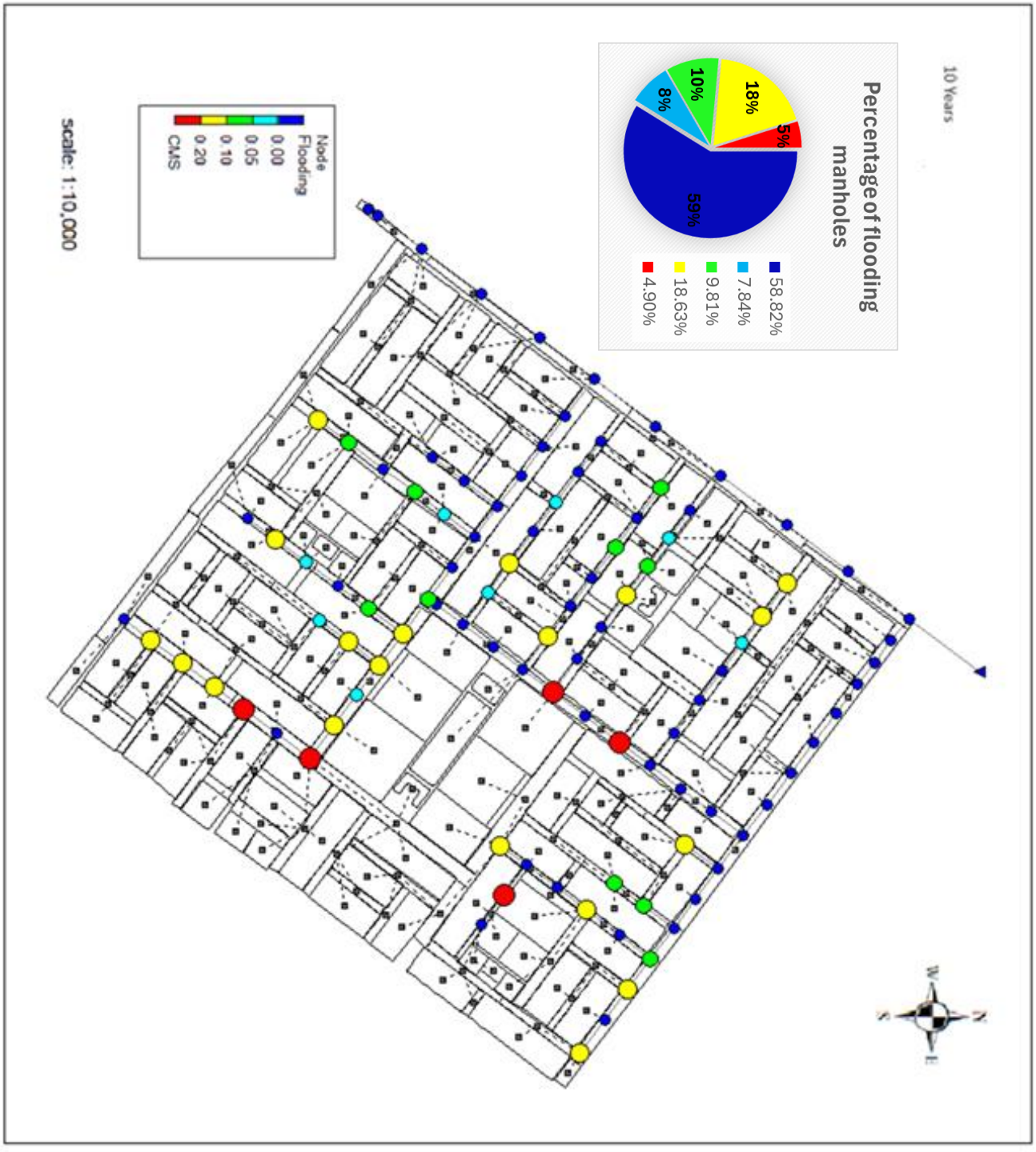


Figure 4-9 Al-Wafaa at a ten-year return time, the quarterly assessment of the rainwater network is conducted during stormwater leaks.

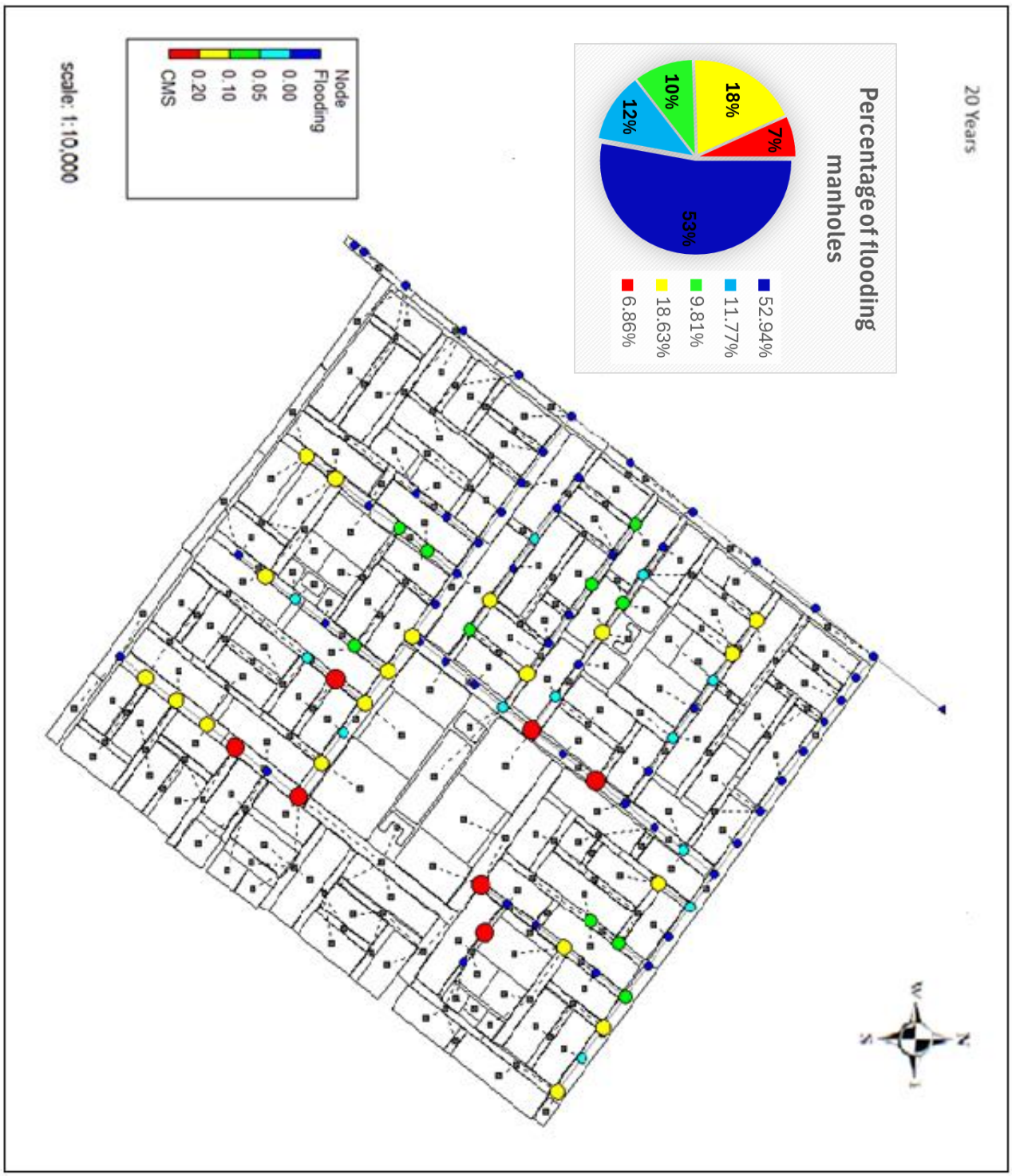


Figure 4-10 Al-Wafaa at a twenty-year return time, the quarterly assessment of the rainwater network is conducted during stormwater leaks.

Flooded manholes were found in most of the main and sub-main stormwater network drains. According to the study (Rabori and Ghazavi, 2018) as the return period increases, the maximum pipe flow increases, which leads to the spread of floods from a few locations to many others. The stormwater drainage system in the Al-Wafa neighborhood was inadequate in managing the substantial water influx during this study, as the inundated manholes reached elevated flood levels in the fifth stage, with ratios varying from 0.98% to 6.86% for return periods of 2, 5, 10, and 20 years, as illustrated in Table (4-6).

Table (4-6) shows the percentage of the five stages mentioned for flooded manholes

Table 4-6 The percentage of the five stages mentioned for flooded manholes.

Stages of flooding manholes	Return period (years)			
	2 years	5years	10 years	20 years
stage1	69.61%	62.74%	58.82%	52.94%
stage2	16.67%	8.82%	7.84%	11.77%
stage3	7.84%	14.72%	9.81%	9.81%
stage4	4.90%	11.76%	18.63%	18.63%
stage5	0.98%	1.96%	4.90%	6.86%

The flood flow rate generated by SWMM modelling varies based on rainfall intensity. Figures 4-7, 4-8, 4-9, and 4-10 represent the flood flow rate from SWMM over 2 hours of simulation time for the rainfall intensity

used. The values and times of maximum flooding resulting from modelling the stormwater drainage network using four different rainfall intensities are listed. As shown in the figures, flood flow starts 15 minutes after the start of the simulation when using all rainfall intensities for the 2- and 5-year return periods, while flood flow starts 10 minutes after the start of the simulation when using rainfall intensities for the 10- and 20-year return periods. Also, the maximum flood flow occurs using a rainfall intensity with a return period of 20 years.

The flood duration for the return period was 2 years (10 minutes), and the maximum flood value in this period was equal to (0.2 m^3/s), which occurred in the manholes (HR15). The flood duration for the return period was 5 years (25 minutes), the maximum flood value was (0.23 m^3/s), and the flood was in the manholes (HR15).

When using the 10-year return rainfall intensity, the flood duration was (40 minutes) and the maximum flood value was (0.26m^3/sec) and the manholes in which the maximum flood occurred were (HR15, HR17, HR90, HR109, HR111) while the flood duration in the return period was 20 year (55 minutes) and its value was (0.29 m^3/sec) which occurred in the manholes (HR12, HR15, HR17, HR88, HR90, HR109, HR111)

The node flood's delay time when using the 2-year return rainfall intensity (15 minutes) is due to the low estimated rainfall intensity values for this return period, which are lower than the other rainfall intensity values for the return periods of 5, 10, and 20 years.

The maximum flood flow rate value shown in table (4-4), about 1.079 m^3/s, using the 2-year return rainfall intensity, is the lowest among the maximum flow rate values obtained from the other three rainfall intensity

simulations for 5, 10, and 20-year return periods, which are 1.453m^3/sec, 1.669m^3/sec, and 1.927m^3/sec, respectively.

At 120 minutes, all models show approximately equal flow rates. After this time, the values continue to decrease until the flooding stops when the rainfall flow rate drops to the system design capacity.

The figures show the flooded nodes and their flow rates at the maximum flood flow rate in the SWMM model of the stormwater network system for all rainfall intensities used.

It was observed that this line Figure (4-11) of the rainwater network in the neighborhood flooded at all return periods for 2,5,10,20 years, and the area adjacent to it flooded due to the lack of establishing an integrated network for the neighborhood. A scenario was proposed to add three pipes continuously on the same line and with the same characteristics to alleviate the flooding in this area and reduce the load on the line mentioned as a result of the water being directed to the area directly adjacent to it.

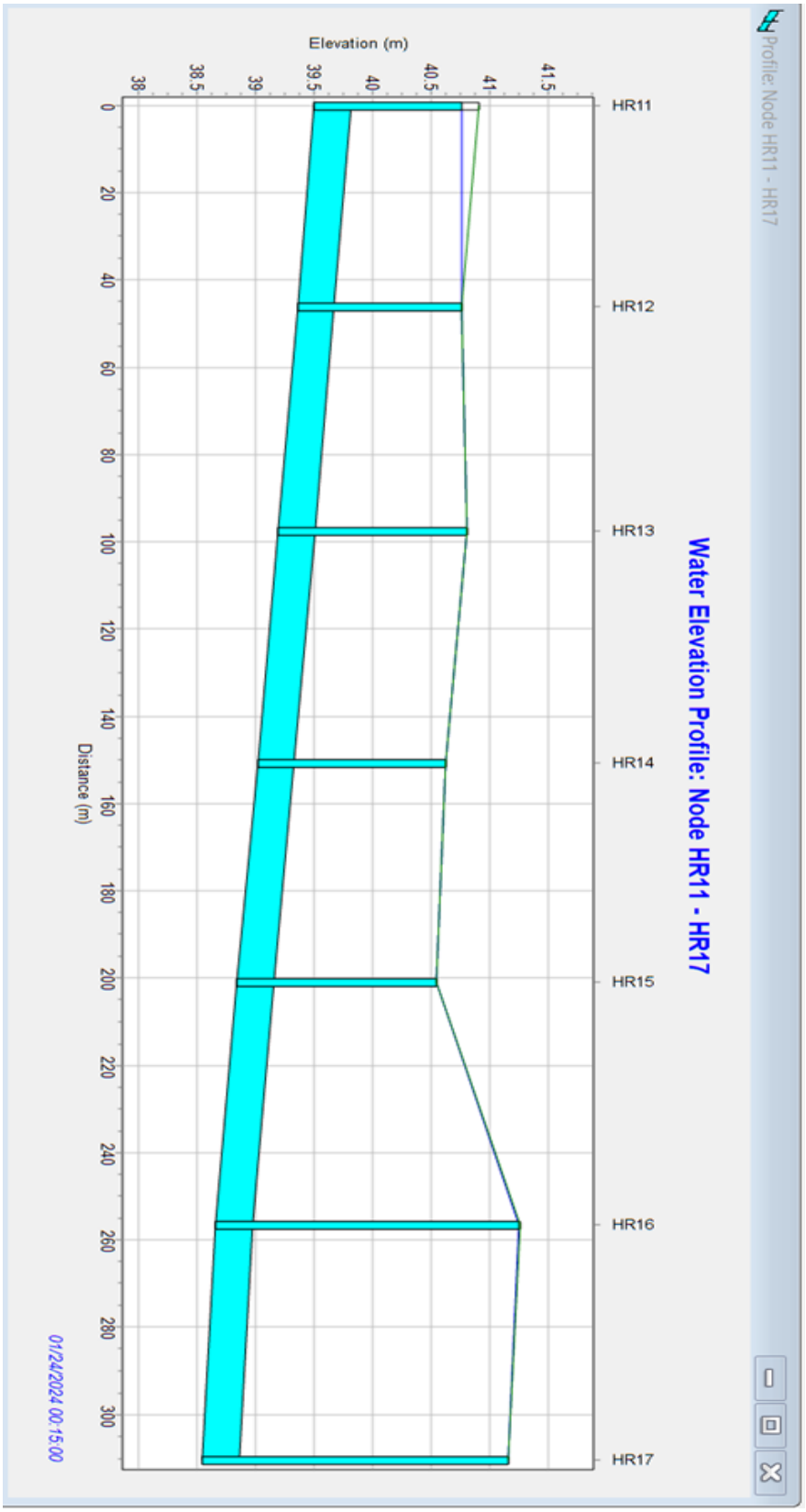


Figure 4-11 water elevation in the manholes

4.3.2 Quantity of stormwater in wet weather flow after adding three pipes to the network

After analyzing the rainwater network in the Al-Wafa neighborhood during rainfall, the results showed flood limits in the neighborhood. Therefore, it was suggested to add three lines with a length of (51,52,55) meters to the network, as shown in Figure (4-12), with diameters of 315 mm, with the aim of reducing floods in the network during rainfall. The results showed that floods decreased relatively after adding these three pipes.

A decrease in the flood volume was observed through figures (4-13) to (4-16), which show the network shape and the number of sewer openings at different recurrence periods (2,5,10,20 years) consecutively after two hours of rainfall. The analyses also showed that adding these lines improved the network's ability to drain rainwater, reducing the hydraulic pressure on the existing pipes and limiting water accumulation in low-lying areas.

Additionally, hydraulic simulations showed that the distribution of flows within the network became more balanced after the addition, reducing the likelihood of blockages or excess water accumulation that could affect drainage efficiency. Analysis of the flow results indicates that this addition improved the network's response during heavy rainfall, enhancing the system's long-term efficiency and reducing the negative impacts of flooding on neighbourhood infrastructure.

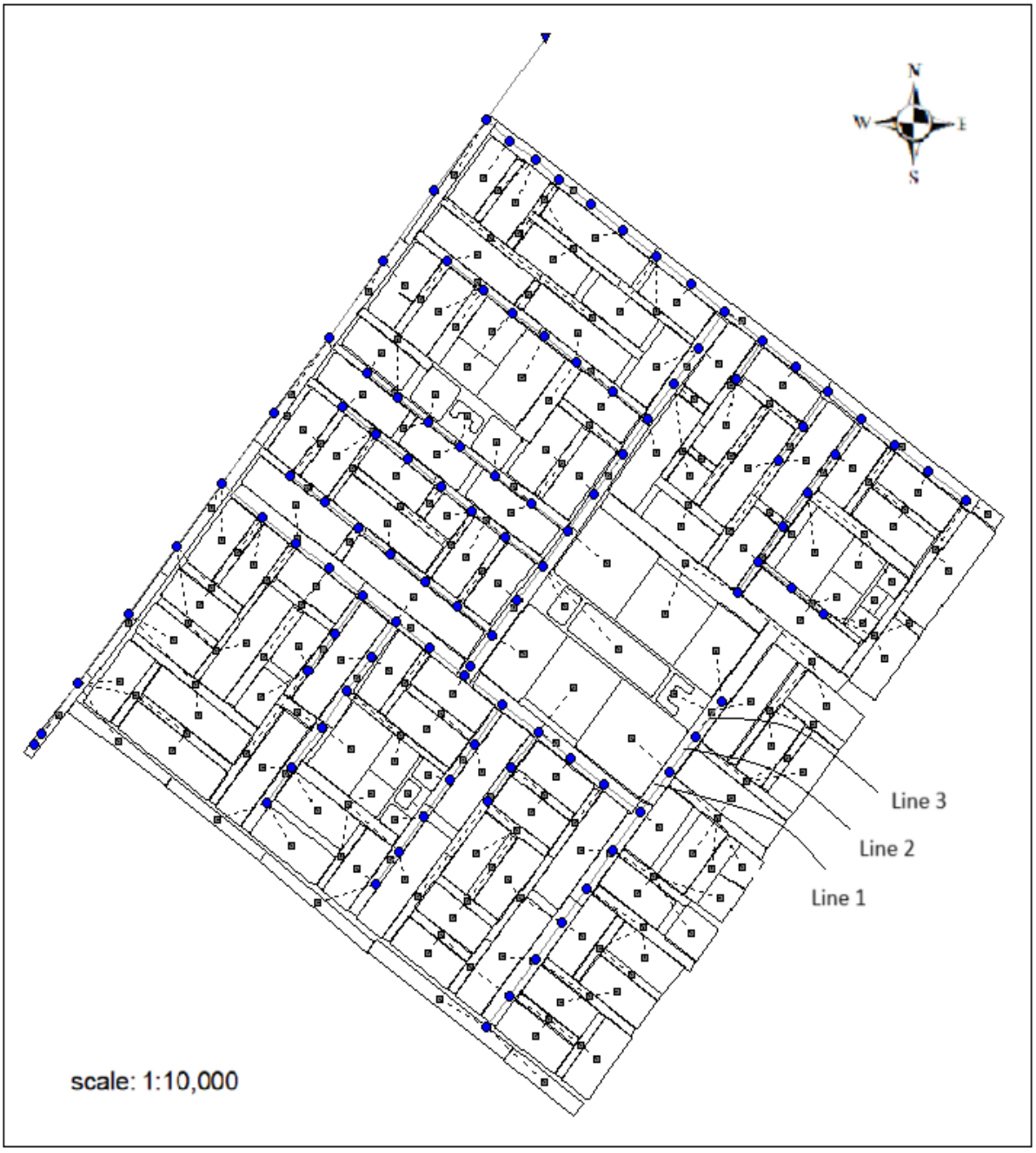


Figure 4-12 The rainwater network in the Al-Wafaa neighborhood with proposed solutions to add three additional lines

Figure (4-13) shows the rainwater network of the Al-Wafaa neighborhood after adding the three proposed pipes during a return period of 2 years during rainfall where it was noted that the decrease occurred in the third stage (Moderate flooding). The fifth stage (Very high flooding), where the percentage of flooded manholes decreased in the third stage from 7.84 % to 6.86%, while the flood ended in the fifth stage and became 0% after it was 0.98%, and as a result, the percentage of non-flooded sewage openings increased from 69.61% to 70.60% of the total sewage openings. In the five-year return period, the fourth and fifth stages decreased

Figure (4-14) shows that the percentage of flooded drains in the fourth stage decreased from 11.76% to 9.8%, while the flood in the fifth stage decreased from 1.96% to 0.98%. As a result, the percentage of non-flooded drains increased from 62.74% to 64.70% of the total drains.

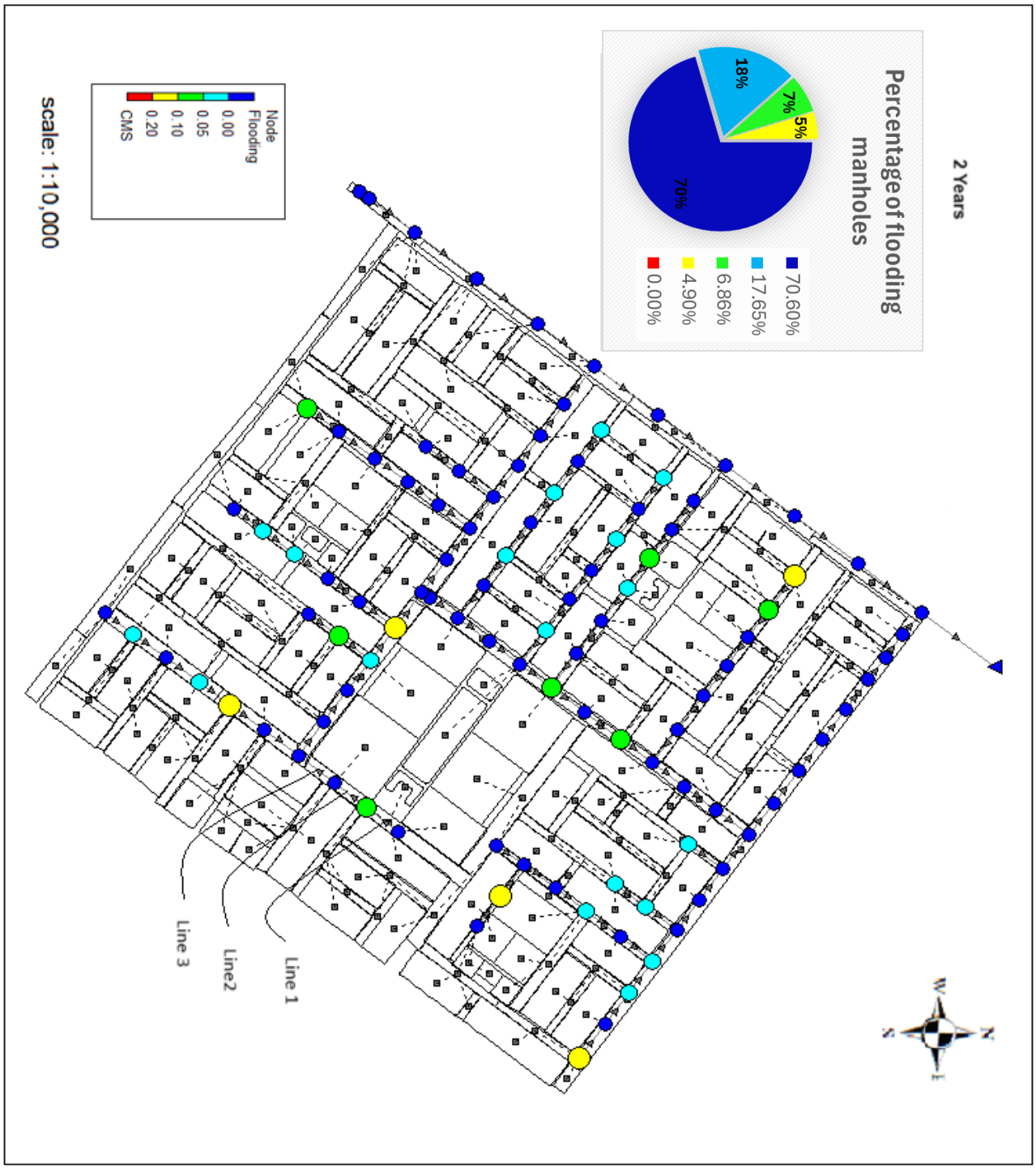


Figure 4-13 The rainwater network in the Al-Wafaa neighbourhood with proposed solutions to add three additional lines at a two-year return period .

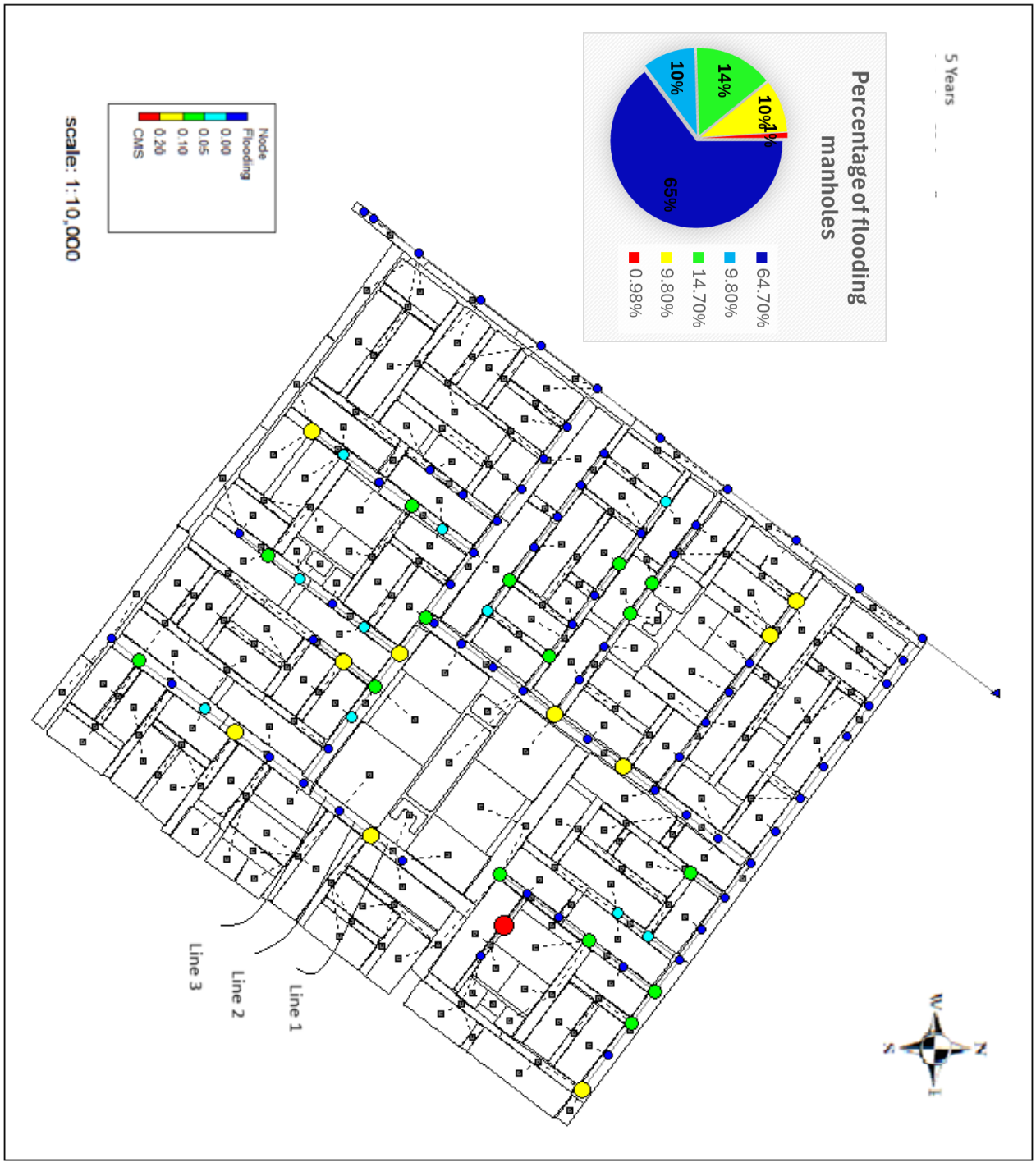
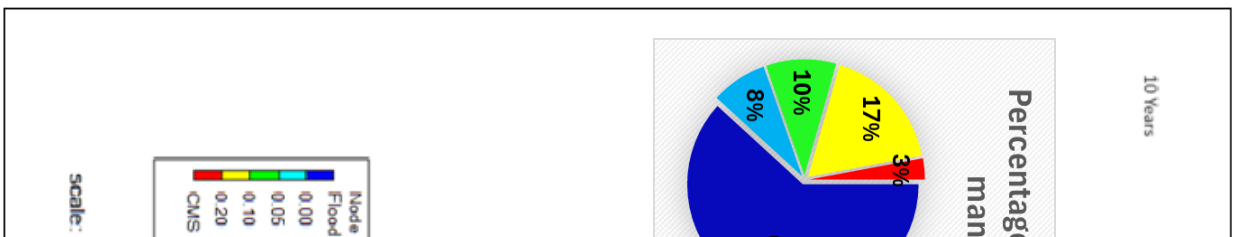


Figure 4-14 The rainwater network in the Al-Wafaa neighborhood with proposed solutions to add three additional lines at a five-year return period .

Figure (4-15) shows the rainwater network in the return period of 10 years, where the fourth stage (extreme flooding) and the fifth stage (very high flooding) decreased. The percentage of flooded drains in the fourth stage decreased from 18.63% to 17.64%, while the flood percentage decreased in the five stages from 4.90% to 2.94%, and as a result, the percentage of non-flooded drains increased from 58.82% to 61.78% of the total drains.

The figure (4-16) shows that the percentage of flooded manholes decreased in the third stage from 9.81% to 8.82%, in the fourth stage from 18.63% to 14.7%, and in the fifth stage from 6.86% to 4.9%, after adjusting the return periods to 20 years and the rainfall intensity to 86.3 mm/hr. In contrast, the percentage of non-flooded manholes increased from 52.94% to 58.84% under the same conditions.



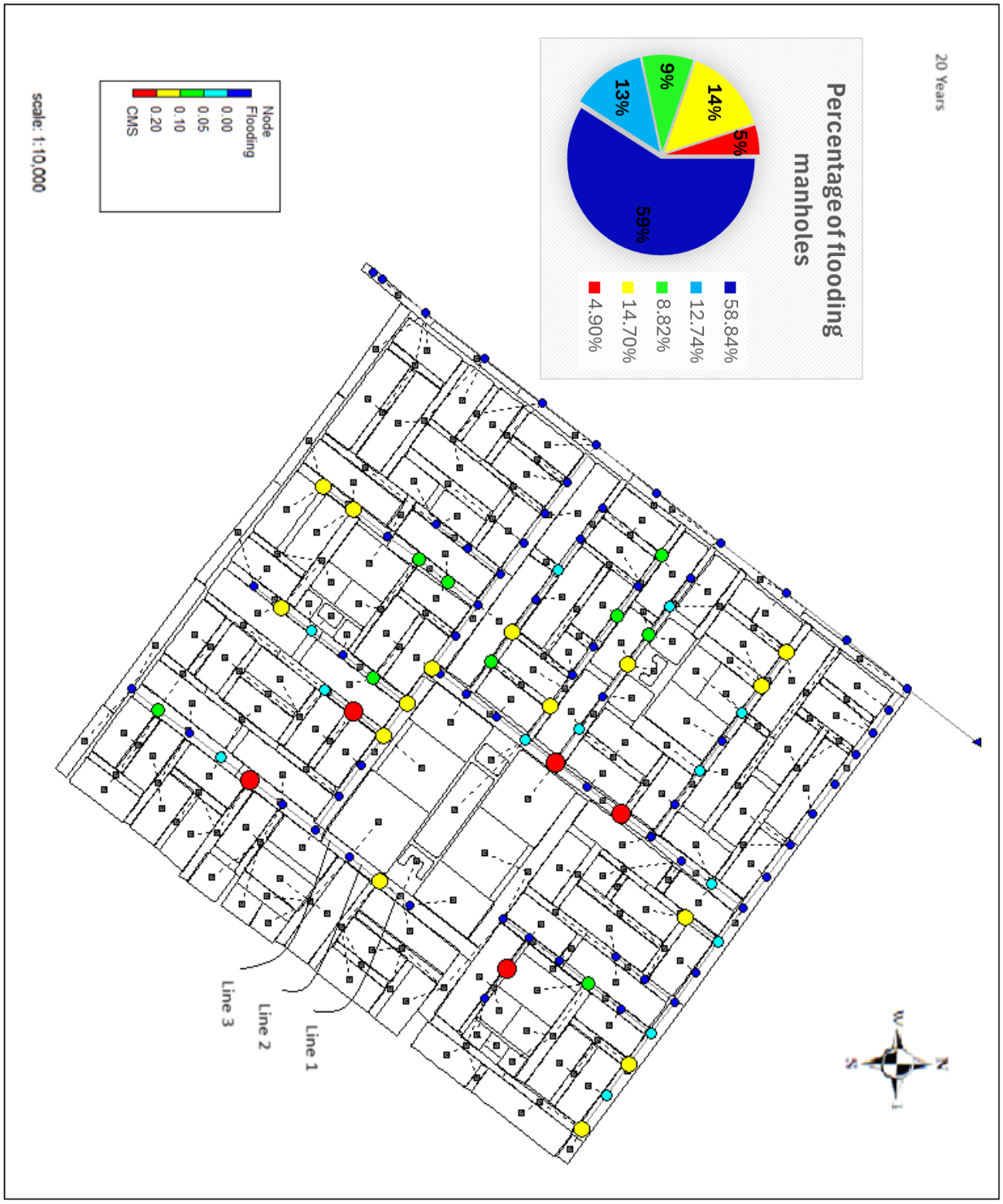


Figure 4-16 The rainwater network in the Al-Wafaa neighborhood with proposed solutions to add three additional lines at a twenty-year return period.

Table (4 -7) shows the percentage of the five stages mentioned for flooded manholes after adding three additional pipes

Table 4-7 The percentage of the five stages mentioned for flooded manholes after adding three additional pipes.

Stages of flooding manholes	Return period (years)			
	2 years	5years	10 years	20 years
stage1	70.60%	64.70%	61.78%	58.84%
stage2	17.65%	9.80%	7.84%	12.74%
stage3	6.86%	14.70%	9.80%	8.82%
stage4	4.90%	9.80%	17.64%	14.70%
stage5	0.00%	0.98%	2.94%	4.90%

The table (4-8) shows the amount and percentage of flood reduction in the rainwater drainage network. It was noted that the number of sewage openings decreased after the addition, and the intensity of rain increased by 12.5% over a return period of twenty years, which is the highest percentage.

Table 4-8 The effect of rainfall events on Al-Wafaa Quarter MR-44 by adding three additional lines to the network.

Return Interval (Years	Duration (Hours)	Maximum flowrate (m3/s)	Total flood volume. (m^3)	Number of Flooded Manholes	Reduction in Manhole Flooding (%)	Maximum Flowrate Percentage (%)	Total Flood Volume Percentage (%)
2	2	0.88	4952	30	3.23	18.44	28.45
5	2	1.4	8400	36	5.26	3.65	0.49
10	2	1.65	9231	39	7.14	1.14	0.17
20	2	1.902	9878	42	12.50	1.31	0.78

During the two-year return period, the network's maximum flow rate was 0.88 m³/s, the total flood volume was 4,952 m³, and 30 manholes were flooded. During the five-year return period, the network's maximum flow rate was 1.4 m³/s, the total flood volume was 0.49%, and 36 manholes were flooded.During the ten-year return period, the highest flow rate percentage was 1.14%, the total flood volume rose to 9231 m³, and the number of inundated manholes grew by 39. Over the 20-year return period, the number of flooded manholes rose to 42, with a peak flow rate of 1.902 m³/s and a cumulative flood volume of 9878 m³.

Table 4-9 After the three pipelines are added, each return period's phases of inundated manholes

Flooding stages manholes / Return period (years)	Stage 1 Before 3 pipes %	Stage 1 After 3 pipes %	Stage 2 Before 3 pipes %	Stage 2 After 3 pipes %	Stage 3 Before 3 pipes %	Stage 3 After 3 pipes %	Stage 4 Before 3 pipes %	Stage 4 After 3 pipes %	Stage 5 Before 3 pipes %	Stage 5 After 3 pipes %
2years	69.61	↑70.60	16.67	17.65	7.84	↓6.86	4.90	4.90	0.98	↓0
5years	62.74	↑64.70	8.82	9.80	14.72	↓14.70	11.76	↓9.80	1.96	0.98
10years	58.82	↑61.78	7.84	7.84	9.81	↓9.80	18.63	↓17.64	4.90	↓2.94
20years	52.94	↑58.84	11.77	12.74	9.81	↓8.82	18.63	↓14.70	6.86	↓4.90

*Stage 1 (No flooding)
*Stage 2 (Very mid-flooding)
*Stage 3 (Moderate flooding)
*Stage 4 (Extreme flooding)
*Stage 5 (Very hight flooding)
* ↑: [increased], ↓: [decreased].

The percentages of decrease and increase in the flood rate of the rainwater network were summarized in Table (4-9). The table shows the five stages of floods, before and after adding the three pipes to the network, in different return periods of 2.5, 10, and 20 years, as explained previously.

4.3.3 The quantity of stormwater that flows during rainy weather for the Low Impact Development (LID)

The LID technology was added to the rainwater network in the Al-Wafa neighborhood as one of the proposed solutions to reduce flooding in the network. The effectiveness of this method and its impact on flooding in the neighborhood were observed. Thus, this method was modeled for different return periods for (2,5,10,20) years through the figures (4-17) to (4-20) and with different rainfall intensities.

Figure (4-17) shows that MR-44 in the Al-Wafaa neighborhood, after two years, for two hours, and after adding LID, the flood rates were divided

into five stages as shown, where the figure it shows that the flooded manholes decreased by16.67% to 7.84% in the second stage, while the percentage decreased in the third stage from 7.84% to 2.94%. In the fourth stage, it decreased from 4.90% to 2.94%, while in the fifth stage, the percentage became 0% after it was 0.98%. The percentage increased in the first stage (the percentage of non-flooded manholes) from 69.61% to 86.27%.

Figure (4-18) shows that the percentage of flooded manhole openings in the third phase decreased to 11.76 % after being 14.72 % for five years. The percentage decreased in the fourth phase from 11.76% to 8.82%, and in the fifth stage, it decreased from 1.96% to 0.98%. Meanwhile, the percentage of non-flooded manholes increased from 62.74% to 68.64% of the total manholes.

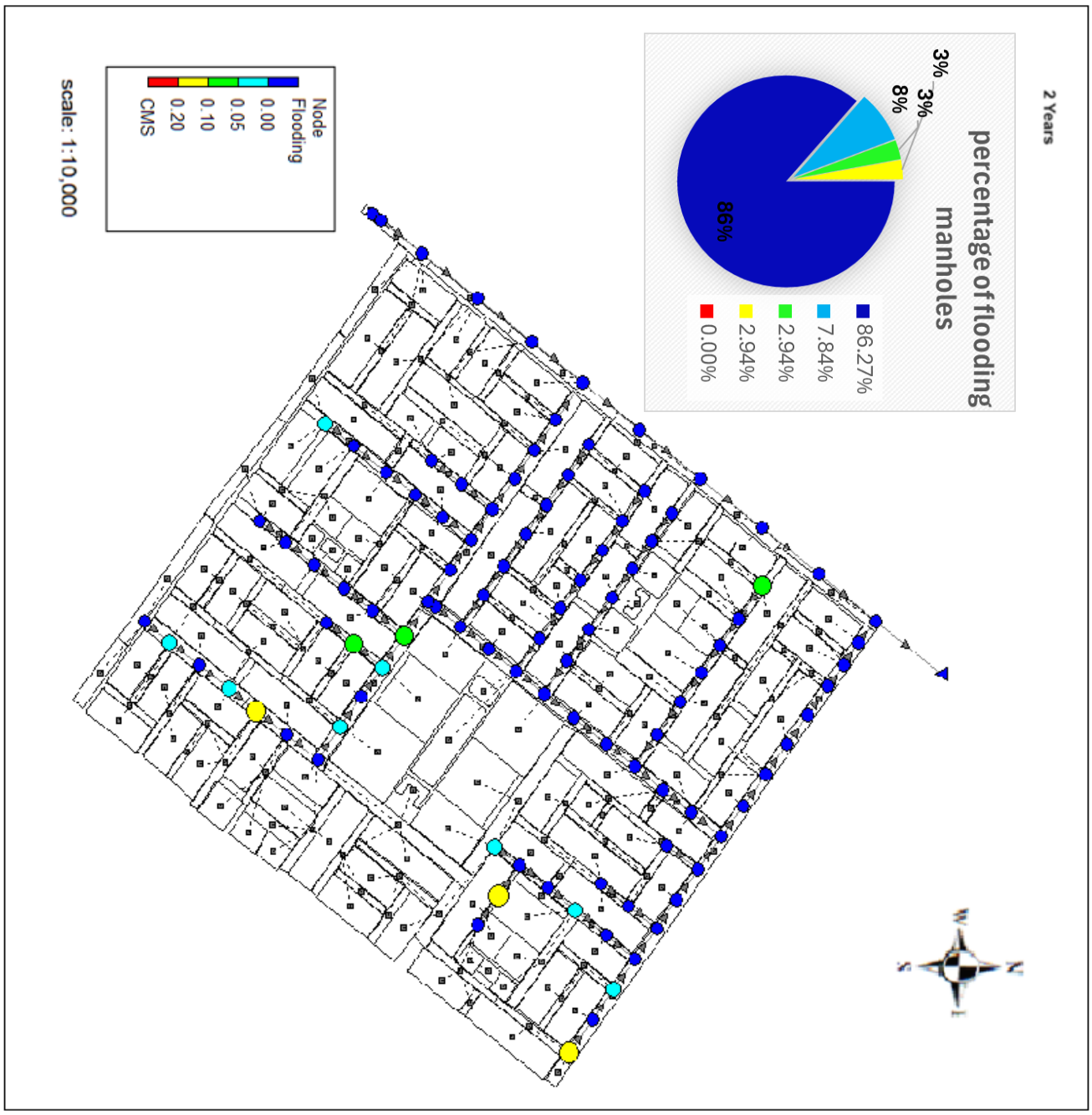


Figure 4-17 Rainwater network in the Al-Wafaa neighborhood after adding LID technology, with a return period of two years, as proposed solutions.

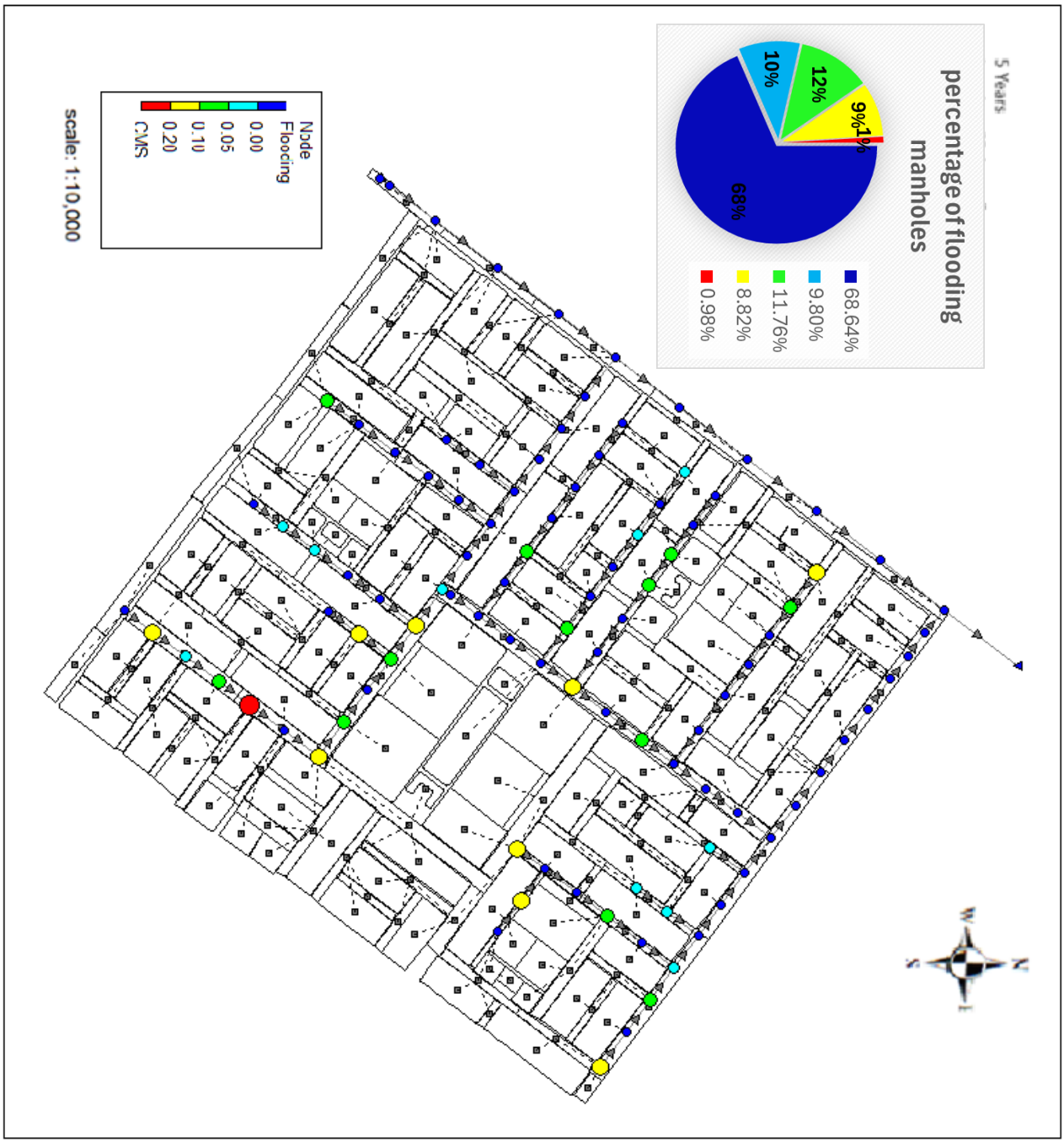


Figure 4-18 Rainwater network in the Al-Wafaa neighborhood after adding technology LID with a return period of 5 years as proposed solutions.

Figure (4-19) shows that, where a decrease was observed in the percentage of flooded openings in the fourth stage from 18.63% to 11.76%, and the fifth stage, the percentage decreased from 4.90% to 1.96% On the other hand, the percentage of non-flooded openings increased from 58.82% to 63.74%.

When the return period was adjusted to 20 years, Figure (4-20) shows a decrease in the percentage of flooded openings in the second stage from 11.77% to 8.82%, while in the fourth stage, the percentage decreased from 18.63% to 14.70%, and in the fifth stage, it decreased from 6.86% to 4.90%. The percentage of non-flooded manholes reached 60.80% after 52.94%, as the percentage increased after adding LID,

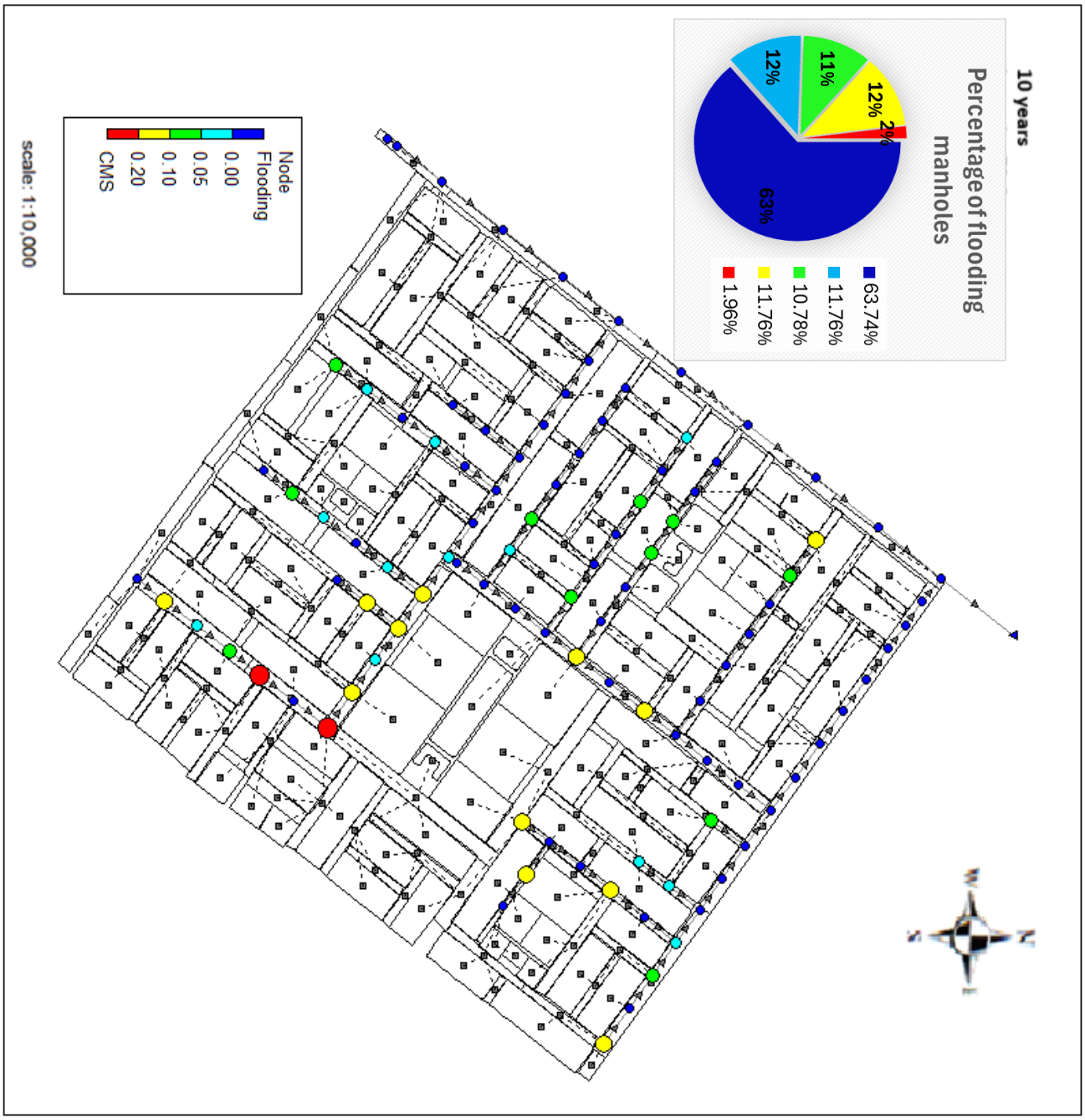

10 years
Percentage of flooding manholes
63%
12%
11%
12%
2%
1.96%
11.76%
10.78%
11.76%
63.74%
Node Flooding
CMS
0.00
0.05
0.10
0.20
scale: 1:10,000

Figure 4-19 Rainwater network in the Al-Wafaa neighborhood after adding LID technology, with a return period of ten years, as proposed solutions.

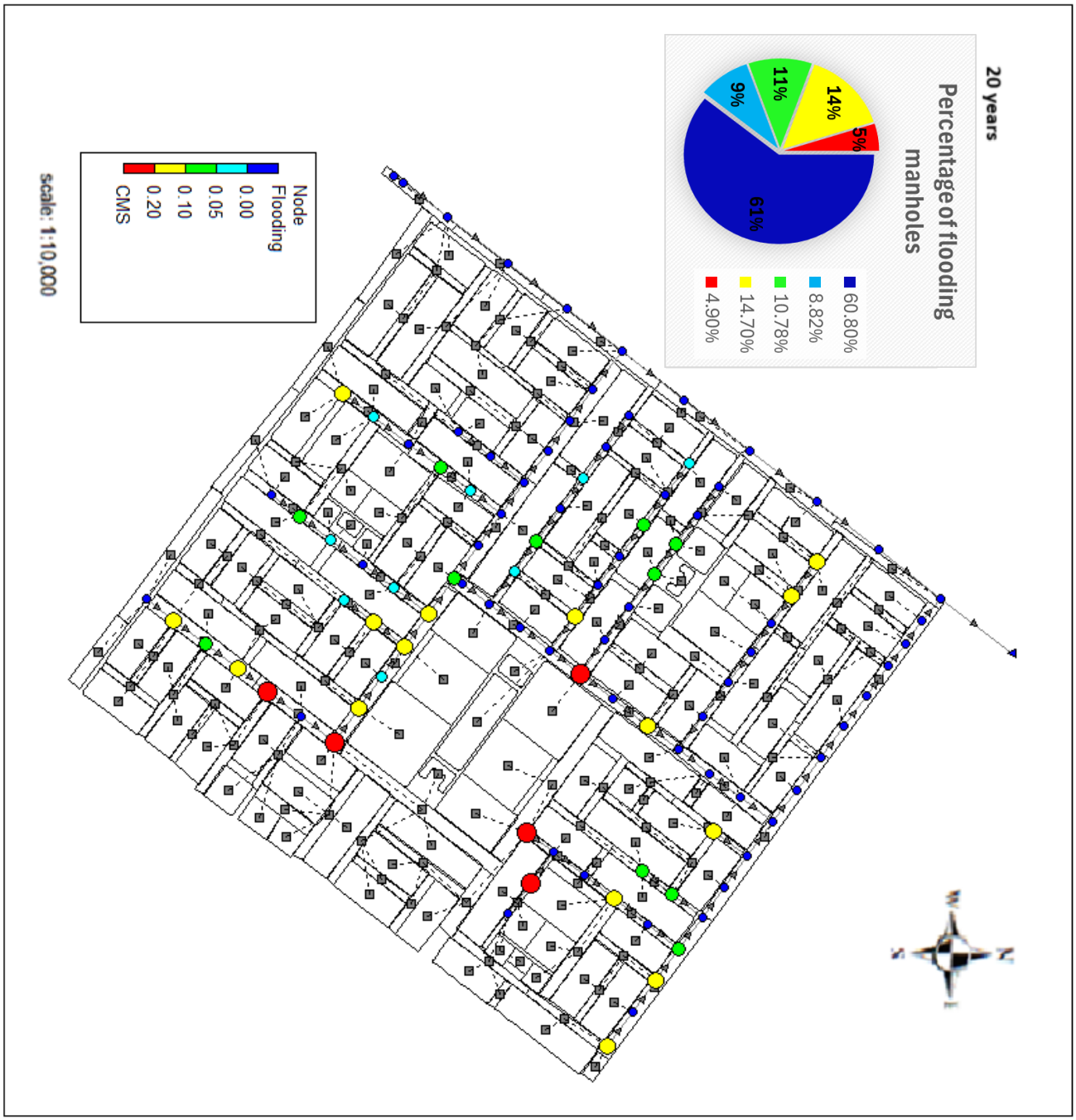


Figure 4-20 Rainwater network in the Al-Wafaa neighborhood after adding LID technology, with a return period of twenty years, as proposed solutions.

The table (4-10) shows the changes that occurred in the percentage of flooded and non-flooded manholes for all periods.

Table 4-10 The percentage of the five stages mentioned for flooded manholes with LID.

Stages of flooding manholes	Return period (years)			
	2 years	5years	10 years	20 years
stage1	86.27%	68.64%	63.74%	60.80%
stage2	7.84%	9.80%	11.76%	8.82%
stage3	2.94%	11.76%	10.78%	10.78%
stage4	2.94%	8.82%	11.76%	14.70%
stage5	0.00%	0.98%	1.96%	4.90%

The simulation results were analyzed before and after the addition of LID techniques, showing the effect of the suggested solutions on increasing network performance. Table (4-11) shows the design efficiency of the MR-44 with the addition of low-impact design (LID) measures. The table includes the maximum water flow rate in the stormwater drainage network, the total flood volume, and the number of closed outlets for return periods of 2, 5, 10, and 20 years, with a two-hour rainfall period.

Table 4-11 Rainfall and its impact on the Al-Wafaa neighborhood using technology LID

Return Interval (Years	Duration (Hours)	Maximum flowrate (m3/s)	Total flood volume. (m^3)	Number of Flooded Manholes	Reduction in Manhole Flooding (%)	Maximum Flowrate Percentage (%)	Total Flood Volume Percentage (%)
2	2	0.966	6110	14	54.84	10.473	11.72
5	2	1.171	7471	32	15.79	19.408	11.49
10	2	1.402	8194	37	11.90	15.998	11.39
20	2	1.608	8808	40	16.67	15.457	11.53

After adding LID, the flood results before treatment were compared with the flood results after treatment and adding LID, where the percentage of decrease in the total flood volume was 11.72% and 10.47% in the maximum flow rate and 54.84% in the total flood openings during the return period of two years as shown in the table (4-12).

In 5 years, a decrease in the flood volume was recorded by 11.49 %, a percentage decrease in the maximum flow rate reached 19.41%, and a decrease in the number of flooded manholes achieved 15.79% of the total flood manhole.

For the ten years, the percentage of decrease in the flood volume reached 11.39%, and the maximum flow rate decreased by 15.99% while the number of flood openings decreased to 11.9 % of the total flooded manholes.

In the twenty-year return period, the total flood volume decreased to 11.53%, the maximum flow rate decreased by 15.46%, and the percentage of the number of flooded manholes decreased to 16.67 % of the total sewage openings. These results made it clear that the proposal to add LID to MR-44 has significantly affected the flood results in the Al-Wafa neighborhood and reduced it.

Table 4-12 The flooded manhole phases are included for each return period following the addition of LID.

Flooding stages manholes / Return period (years)	Stage 1 Before LID %	Stage 1 After LID %	Stage 2 Before LID %	Stage 2 After LID %	Stage 3 Before LID %	Stage 3 After LID %	Stage 4 Before LID %	Stage 4 After LID %	Stage 5 Before LID %	Stage 5 After LID %
2years	69.61	↑86.27	16.67	↓7.84	7.84	↓2.94	4.90	↓2.94	0.98	↓0
5years	62.74	↑68.64	8.82	9.80	14.72	↓11.76	11.76	↓8.82	1.96	↓0.98
10years	58.82	↑63.74	7.84	11.7	9.81	10.78	18.63	↓11.76	4.90	↓1.96
20years	52.94	↑60.80	11.77	↓8.82	9.81	10.78	18.63	↓14.70	6.86	↓4.90

*Stage 1 (No flooding)
*Stage 2 (Very mid-flooding)
*Stage 3 (Moderate flooding)
*Stage 4 (Extreme flooding)
*Stage 5 (Very hight flooding)
* ↑: [increased], ↓: [decreased].

Table (4-12) shows the percentages of decrease and increase in the five flood stages of the rainwater network before adding the technology LID and after adding it at different return periods of 2,5,10 and 20 years. A clear change was observed in most of the percentages for the five different stages after adding the technology LID to the network and an increase in the percentages of non-submerged manholes, which indicates the efficiency of this technology in reducing flood rates significantly.

It was noted that the proposal to add the LID is consistent with some previous studies, including the study in which it was proposed to add rain gardens to MS4 to reduce the size of the flood that reached $46.56*10^6$L over five years, and thus led to reducing the number of flooded sewer openings to 87 (Zhang et al., 2020)This indicates that rain gardens work very well with the floods that occur during heavy rainfall in the NakagyoWard area for five years in Kyoto, Japan.

In Suqian City, China, the LID facilities in Sucheng District include a rain garden, concave green belt, permeable pavement, and green roof (Bai et al., 2019). Four scenarios were evaluated, each of which involved altering one facility's area ratio while maintaining the other facilities' respective areas.The study demonstrated the effectiveness of using LID facilities, showing that runoff and peak flow reduction rates increased from 30.4% and 27.1% to 44.1% and 40.3% in scenarios involving different rain garden ratios.

Generally, the runoff network of the area under investigation functions satisfactorily in its present condition and the years to come. Cleaning and cleansing this item regularly and redirecting superfluous water toward nearby green spaces and gardens can help preserve it.

The medium and long-term implications of flood-prone localities in the study area were thoroughly examined. Water resource officials and city stakeholders can implement appropriate mitigation strategies, such as diverting excess water to green areas, modifying slopes, adding pipes, and increasing the depth of floodgates exposed to future flooding. These steps are essential to avoid flood damage to infrastructure. Climate change adaptation and mitigation measures are being implemented, such as low-impact development (LID), with an emphasis on achieving a balance

between environmental and economic impacts to ensure that maintenance costs are less than the potential damage without implementing these measures. This strategy is essential for preparing for imminent climate changes and ensuring the system can manage rainwater effectively during emergency heavy rainfall events through retrofitting and design standards that address the increasing threat of future floods. It is essential, irrespective of the costs that may arise.

4.4 Summary

The risk of flooding in the Al-Wafaa network increases as a result of the activities and habits of the residents, as their behavior affects them in multiple ways. Among these factors is the use of infrastructure, dumping garbage in the entrances of the sewage networks, the accumulation of waste from commercial activities, and the spillage of untreated liquid and solid waste such as car oils, butcher shop waste, and food industry waste such as vegetable markets and vinegar. These factors lead to the blockage of networks, which increases the possibility of flooding limits, and this may lead to the pollution of rainwater during periods of rainfall. These results are consistent with what other researchers have reached, as shown in previous studies, (Sercu et al., 2011), (Sauer et al., 2011), (Obaid et al., 2014) , (Ward and Winter, 2016), (Hassan et al., 2017) and (Salerno et al., 2018) .

The lack of regular maintenance of rainwater networks, the inadequacy of municipal waste collection services, and the significant increase in population growth in the study area increase the pressure on the network.

To simulate the effects of rainwater on the rainfall network in Kerbala Governorate, the study employed physical and statistical models. The

SWMM software demonstrated reasonable modeling ability in representing future extreme precipitation events. The study identified the areas most susceptible to urban inundation by examining the behavior of the rainwater networks in near, medium, and far future events.

The results show that the best method for reducing flooding to a greater extent is the LID technology, which is followed in many countries to reduce flooding from rainwater. Therefore, it is considered an environmental aesthetic for the region and also less harmful and costly than other additions to the network and improves its performance.

Chapter Five: Conclusion and Recommendations

5.1 Conclusion

The results presented in Chapter Four were the basis for the development of numerous conclusions in this chapter. This can be elucidated as follows:

1-The calibration of the network water quantities in the program SWMM and during a real event was very good because the verification results that appeared in the value NMSE for the periods 2,5,10, and 20 years were 1.16,0.998,0.97 and 0.93, respectively very similar to the ideal fit. Also, the values R^2 for periods 2,5,10, and 20 years, which were 0.93,0.97,0.957, and 0.899, respectively, indicated a very strong correlation between the real and measured data.

2- The simulation shows that in the case of befor storm, no flooding occurs in the network of the study area. In contrast, in the case of wet weather and continuous rainfall with high rainfall intensity, the drainage system of the stormwater network will be exposed to flooding.

3- The results obtained from this study on the study area can greatly help the concerned parties know the exact location of the flood in any manholes in the neighborhood and thus help develop plans and solutions to mitigate this flood.

4-When three pipes were added to the stormwater network in the Al-Wafaa district, this reduced the intensity of the flood and the maximum flow rate by 6.135% as well as the total flood volume rate by 7.47%, the number

of flooded manhole rates by 7.03% during the return period of 2,5,10,20 years.

5- It is an essential method for understanding the impact of various operational factors on a stormwater network. The sub-catchment parameters have been painstakingly adjusted through trial and error to mitigate the discrepancy between the modelled and measured discharges. The critical characteristics are manning's roughness, impervious per cent factor, coefficient, sub-catchment diameter, and sub-catchment surface slope.

6- Adding the LID technology, as proposed in the Al-Wafa neighborhood, was more effective in reducing flooding and is considered a very important technology in urban areas because it solves the problem of impermeability in some surfaces of the neighborhood as the maximum flow rate decreased by 15.33% and the total flood volume rate by 11.53%, and the number of flooded manholes rate by 24.8% during the return period of 2,5,10,20 years.

5.2 Recommendations

1. In the future, it is preferable to adopt alternative methods to reduce the amount of water entering MR-44 during rainfall, as only one type of LID technology was used in the area covered by the study despite the existence of other technologies available. Therefore, it is recommended to evaluate the effectiveness of alternative LID technologies.

2.It is recommended to compare the costs between the types of techniques LID in the study area.

References

!!! INVALID CITATION !!! (Federation and . 1998, Prevention, 2005, Arnold Jr and Gibbons, 1996).

ABBAS, A., RUDDOCK, F., ALKHADDAR, R., ROTHWELL, G. & ANDOH, R. 2019. Improving the geometry of manholes designed for separate sewer systems. *Canadian Journal of Civil Engineering*, 46**,** 13-25.

ACKERMAN, D. & STEIN, E. D. 2008. Evaluating the effectiveness of best management practices using dynamic modeling. *Journal of Environmental Engineering*, 134**,** 628-639.

ADAMS, B. J. 2000. Urban stormwater management planning with analytical probabilistic models.

ADEYI, G., ADIGUN, A., ONYEOCHA, N. & OKEKE, O. 2020. Unit hydrograph: concepts, estimation methods and applications in hydrological sciences. *Int. J. Eng. Sci. Comput*, 10**,** 26211-26217.

AFRIN, S., ISLAM, M. & RAHMAN, M. 2021. Adequacy assessment of an urban drainage system considering future land use and climate change scenario. *Journal of Water and Climate Change*, 12**,** 1944-1957.

AHIABLAME, L. M., ENGEL, B. A. & CHAUBEY, I. 2013. Effectiveness of low impact development practices in two urbanized watersheds: Retrofitting with rain barrel/cistern and porous pavement. *Journal of environmental management*, 119**,** 151-161.

AHMED, K., CHUNG, E.-S., SONG, J.-Y. & SHAHID, S. 2017. Effective design and planning specification of low impact development practices using Water Management Analysis Module (WMAM): Case of Malaysia. *Water*, 9**,** 173.

ALFREDO, K., MONTALTO, F. & GOLDSTEIN, A. 2010. Observed and modeled performances of prototype green roof test plots subjected to simulated low-and high-intensity precipitations in a laboratory experiment. *Journal of Hydrologic Engineering*, 15**,** 444-457.

ALYASERI, I., ZHOU, J. & MORGAN, S. Sustainable stormwater management using rain gardens in urban areas. IOP Conference Series: Earth and Environmental Science, 2021. IOP Publishing, 012041.

ANDERSEN, C., FOSTER, I. D. & PRATT, C. J. 1999. The role of urban surfaces (permeable pavements) in regulating drainage and evaporation: development of a laboratory simulation experiment. *Hydrological processes,* 13**,** 597-609.

ARNOLD JR, C. L. & GIBBONS, C. J. 1996. Impervious surface coverage: the emergence of a key environmental indicator. *Journal of the American planning Association,* 62**,** 243-258.

ASKARIZADEH, A., RIPPY, M. A., FLETCHER, T. D., FELDMAN, D. L., PENG, J., BOWLER, P., MEHRING, A. S., WINFREY, B. K., VRUGT, J. A. & AGHAKOUCHAK, A. 2015. From rain tanks to catchments: use of low-impact development to address hydrologic symptoms of the urban stream syndrome. *Environmental science & technology,* 49**,** 11264-11280.

BAI, Y., LI, Y., ZHANG, R., ZHAO, N. & ZENG, X. 2019. Comprehensive performance evaluation system based on environmental and economic benefits for optimal allocation of LID facilities. *Water,* 11**,** 341.

BAI, Y., ZHAO, N., ZHANG, R. & ZENG, X. 2018. Storm water management of low impact development in urban areas based on SWMM. *Water,* 11**,** 33.

BALLESTERO, T. P., HOULE, J. J. & PULS, T. A. 2016. Breaking Through: University Of New Hampshire Stormwater Center 2016 Report.

BANNERMAN, R. T., OWENS, D. W., DODDS, R. & HORNEWER, N. J. 1993. Sources of pollutants in Wisconsin stormwater. *Water Science and technology,* 28**,** 241-259.

BARCO, J., WONG, K. M. & STENSTROM, M. K. 2008. Automatic calibration of the US EPA SWMM model for a large urban catchment. *Journal of Hydraulic Engineering,* 134**,** 466-474.

BARLOW, D., BURRILL, G. & NOLFI, J. R. 1977. *A research report on developing a community level natural resource inventory system*, Center for Studies in Food Self-Sufficiency, Vermont Institute of Community ….

BEIRO, T. S. & MANSO, A. S. 2012. Modelling and Analysis of Urban Flooding in Lundby-Kyrkbyn, Göteborg.

BHADURI, B., MINNER, M., TATALOVICH, S. & HARBOR, J. 2001. Long-term hydrologic impact of urbanization: a tale of two models. *Journal of Water Resources Planning and Management,* 127**,** 13-19.

BIBI, T. S., REDDYTHTA, D. & KEBEBEW, A. S. 2023. Assessment of the drainage systems performance in response to future scenarios and

flood mitigation measures using stormwater management model. *City and Environment Interactions,* 19**,** 100111.
BIZIER, P. 2007. *Gravity sanitary sewer design and construction*, Water Environment Foundation (WEF).
BOUGHTON, W. & DROOP, O. 2003. Continuous simulation for design flood estimation—a review. *Environmental Modelling & Software,* 18**,** 309-318.
BRATH, A., MONTANARI, A. & MORETTI, G. 2006. Assessing the effect on flood frequency of land use change via hydrological simulation (with uncertainty). *Journal of hydrology,* 324**,** 141-153.
BRATTEBO, B. O. & BOOTH, D. B. 2003. Long-term stormwater quantity and quality performance of permeable pavement systems. *Water research,* 37**,** 4369-4376.
BROWN, R., SKAGGS, R. & HUNT III, W. 2013. Calibration and validation of DRAINMOD to model bioretention hydrology. *Journal of hydrology,* 486**,** 430-442.
CAMPOLONGO, F. & BRADDOCK, R. 1999. Sensitivity analysis of the IMAGE Greenhouse model. *Environmental modelling & software,* 14**,** 275-282.
CANTONE, J. & SCHMIDT, A. 2011. Improved understanding and prediction of the hydrologic response of highly urbanized catchments through development of the Illinois Urban Hydrologic Model. *Water Resources Research*, 47.
CARLE, M. V., HALPIN, P. N. & STOW, C. A. 2005. Patterns of watershed urbanization and impacts on water quality 1. *JAWRA Journal of the American Water Resources Association*, 41**,** 693-708.
CHABAEVA, A., CIVCO, D. L. & HURD, J. D. 2009. Assessment of impervious surface estimation techniques. *Journal of Hydrologic Engineering,* 14**,** 377-387.
CHANG, M., MCBROOM, M. W. & BEASLEY, R. S. 2004. Roofing as a source of nonpoint water pollution. *Journal of environmental management,* 73**,** 307-315.
CHARLESWORTH, S., HARKER, E. & RICKARD, S. 2003. A review of sustainable drainage systems (SuDS): A soft option for hard drainage questions? *Geography***,** 99-107.
CHEN, D. & GUO, Z. 2022. The source, transport, and removal of chemical elements in rainwater in China. *Sustainability*, 14**,** 12439.
CHEN, H. 2006. Dean's Message.

CHEN, Y. 2019. *Analysis and evaluation of the effectiveness of Low Impact Development practices on runoff control using Remote Sensing, GIS and hydrological modeling.* Technische Universität Dortmund.

CHEN, Y., SAMUELSON, H. W. & TONG, Z. 2016. Integrated design workflow and a new tool for urban rainwater management. *Journal of environmental management,* 180**,** 45-51.

CHIN, D. A., MAZUMDAR, A. & ROY, P. K. 2000. *Water-resources engineering*, Prentice Hall Englewood Cliffs.

CHINI, C. M., CANNING, J. F., SCHREIBER, K. L., PESCHEL, J. M. & STILLWELL, A. S. 2017. The green experiment: Cities, green stormwater infrastructure, and sustainability. *Sustainability,* 9**,** 105.

DAI, M., ZHAO, Y., CHAI, F., CHEN, M., CHEN, N., CHEN, Y., CHENG, D., GAN, J., GUAN, D. & HONG, Y. 2023. Persistent eutrophication and hypoxia in the coastal ocean. *Cambridge Prisms: Coastal Futures,* 1**,** e19.

DAVIS, A. P., HUNT, W. F., TRAVER, R. G. & CLAR, M. 2009. Bioretention technology: Overview of current practice and future needs. *Journal of environmental engineering,* 135**,** 109-117.

DIETZ, M. E. 2007. Low impact development practices: A review of current research and recommendations for future directions. *Water, air, and soil pollution,* 186**,** 351-363.

DION, T. R. 2002. *Land development for civil engineers*, John Wiley & Sons.

DIVISION, U. S. E. P. A. W. P. 1982. *Results of the nationwide urban runoff program*, Water Planning Division, US Environmental Protection Agency.

DONG, L. 2007. Present status and problems of rainwater utilization plan in some Chinese cities. *CHINA WATER AND WASTEWATER,* 23**,** 1.

DONG, X., GUO, H. & ZENG, S. 2017. Enhancing future resilience in urban drainage system: Green versus grey infrastructure. *Water research,* 124**,** 280-289.

ECKART, K., MCPHEE, Z. & BOLISETTI, T. 2017. Performance and implementation of low impact development–A review. *Science of the Total Environment,* 607**,** 413-432.

ELSEBAIE, I. H. 2012. Developing rainfall intensity–duration–frequency relationship for two regions in Saudi Arabia. *Journal of King Saud University-Engineering Sciences,* 24**,** 131-140.

EPA, U. 2003. Protecting water quality from urban runoff. Washington: National Service Center for Environmental Publications.

ESHELMAN, L. J. 1991. The CHC adaptive search algorithm: How to have safe search when engaging in nontraditional genetic recombination. *Foundations of genetic algorithms.* Elsevier.

FARHAN, S. L., ABDELMONEM, M. G. & NASAR, Z. A. 2018. The urban transformation of traditional city centres: Holy Karbala as a case study. *ArchNet-IJAR: International Journal of Architectural Research,* 12**,** 53.

FASSMAN-BECK, E. & SALEH, F. 2021. Sources and impacts of uncertainty in uncalibrated bioretention models using SWMM 5.1. 012. *Journal of Sustainable Water in the Built Environment,* 7**,** 04021006.

FEDERATION, W. E. & ENGINEERS, A. S. O. C. 1992. *Design and construction of urban stormwater management systems*, American Society of Civil Engineers and Water Environment Federation.

FIELD, R. 2018. *Integrated stormwater management,* CRC Press.

FITZPATRICK, F. A., DIEBEL, M. W., HARRIS, M. A., ARNOLD, T. L., LUTZ, M. A. & RICHARDS, K. D. Effects of urbanization on the geomorphology, habitat, hydrology, and fish index of biotic integrity of streams in the Chicago area, Illinois and Wisconsin. American Fisheries Society Symposium, 2005. Citeseer, 87-115.

FLETCHER, T. D., SHUSTER, W., HUNT, W. F., ASHLEY, R., BUTLER, D., ARTHUR, S., TROWSDALE, S., BARRAUD, S., SEMADENI-DAVIES, A. & BERTRAND-KRAJEWSKI, J.-L. 2015. SUDS, LID, BMPs, WSUD and more–The evolution and application of terminology surrounding urban drainage. *Urban water journal,* 12**,** 525-542.

FU, X. 2012. A study of the application of SWMM on urban storm water simulation. *Zhejiang: Zhejiang Normal University*.

GARCIA-CUERVA, L., BERGLUND, E. Z. & RIVERS III, L. 2018. An integrated approach to place Green Infrastructure strategies in marginalized communities and evaluate stormwater mitigation. *Journal of Hydrology,* 559**,** 648-660.

GIRONÁS, J., ROESNER, L. A., DAVIS, J., ROSSMAN, L. A. & SUPPLY, W. 2009. *Storm water management model applications manual*, Citeseer.

GIRONÁS, J., ROESNER, L. A., ROSSMAN, L. A. & DAVIS, J. 2010. A new applications manual for the Storm Water Management Model(SWMM). *Environmental Modelling & Software,* 25**,** 813-814.

GREER, K. & STOW, D. 2003. Vegetation type conversion in Los Penasquitos Lagoon, California: An examination of the role of watershed urbanization. *Environmental Management,* 31**,** 0489-0503.
GUAN, M., SILLANPÄÄ, N. & KOIVUSALO, H. 2015. Assessment of LID practices for restoring pre-development runoff regime in an urbanized catchment in southern Finland. *Water Science and Technology,* 71**,** 1485-1491.
HASSAN, W. H., NILE, B. K. & AL-MASODY, B. A. 2017. Climate change effect on storm drainage networks by storm water management model. *Environmental Engineering Research,* 22**,** 393-400.
HATT, B. E., FLETCHER, T. D., WALSH, C. J. & TAYLOR, S. L. 2004. The influence of urban density and drainage infrastructure on the concentrations and loads of pollutants in small streams. *Environmental management,* 34**,** 112-124.
HAYES, J., BARFIELD, B., HARP, S., CHALAVADI, M., STEVENS, E., ALEXANDER, M. & BATES, B. Modeling impacts of post development water quality BMPs. 21st Century Watershed Technology: Improving Water Quality and Environment Conference Proceedings, 29 March-3 April 2008, Concepcion, Chile, 2008. American Society of Agricultural and Biological Engineers, 7.
HOU, A., TANG, L. & ZHANG, S. 2007. Impacts of sunken lawn and storage pond on urban flood Beijing. *Water***,** 42-45.
HU, W. 2010. Research on the development of storm water model and its application in piedmont cities. *South China University of Technology. Guangzhou, China. Yan Chen,* 118.
HUBER, W. C. Wet-weather treatment process simulation using SWMM. Watershed Management, 2004. 253-264.
HUSSEIN, A., SHAHID, S. & CHELLIAPAN, K. B. A. 2015. Modelling of sewage quality during rainy season. *Asian Journal of Microbiology, Biotechnology and Environmental Sciences,* 17**,** 593-601.
HYDROLOGY, T. O. T. F. O. 2007. *Highway drainage guidelines*, AASHTO.
ISLAM, S. 2023. Assessment of Storm Drainage System of Fatullah Union Within DND Project Using SWMM Model.
JAFF, D. 2023. Conflict, environmental destruction and climate change: a tragedy in Iraq that demands action. *Medicine, Conflict and Survival,* 39**,** 162-171.

JAMES, W., ROSSMAN, L. A. & JAMES, W. R. C. User's guide to SWMM 5:[based on original USEPA SWMM documentation]. 2010. CHI.

JIN, C., ZHAO, S., YAN, X. & ZHOU, Y. 2010. Impacts of permeable brick and sunken lawn on urban stormwater. *China Water Wastewater,* 1**,** 40-46.

KIM, H. W. & LI, M.-H. 2016. Sustainable stormwater management: examining the role of local planning capacity in mitigating peak surface runoff. *Sustainability,* 8**,** 763.

KIRAZ, M. 2018. *Sustainable water and stormwater management for METU Campus.* Middle East Technical University.

KONG, F., BAN, Y., YIN, H., JAMES, P. & DRONOVA, I. 2017. Modeling stormwater management at the city district level in response to changes in land use and low impact development. *Environmental Modelling & Software,* 95**,** 132-142.

KOUTSOYIANNIS, D. On the appropriateness of the Gumbel distribution for modelling extreme rainfall. Proceedings of the ESF LESC Exploratory Workshop held at Bologna, 2003. 24-25.

LANCASTER, A. 2008. A Simplified Approach for Sizing Green Stormwater Infrastructure in the City of Seattle. *Low Impact Development for Urban Ecosystem and Habitat Protection.*

LAOUACHERIA, F., KECHIDA, S. & CHABI, M. 2019. Modelling the impact of design rainfall on the urban drainage system by Storm Water Management Model. *Journal of Water & Land Development,* 40.

LEE, C. 2005a. Application of rainfall frequency analysis on studying rainfall distribution characteristics of Chia-Nan plain area in Southern Taiwan. *Crop Environ. Bioinf,* 2**,** 31-38.

LEE, J. G., NIETCH, C. T. & PANGULURI, S. 2018. Drainage area characterization for evaluating green infrastructure using the Storm Water Management Model. *Hydrology and earth system sciences,* 22**,** 2615-2635.

LEE, R. K. 2005b. Interpreting storm flow data to determine types of infiltration and inflow. *Pipelines 2005: Optimizing Pipeline Design, Operations, and Maintenance in Today's Economy.*

LI, C., LIU, M., HU, Y., GONG, J. & XU, Y. 2016. Modeling the Quality and Quantity of Runoff in a Highly Urbanized Catchment Using Storm Water Management Model. *Polish Journal of Environmental Studies,* 25.

LINE, D., BROWN, R., HUNT, W. & LORD, W. 2012. Effectiveness of LID for commercial development in North Carolina. *Journal of Environmental Engineering,* 138**,** 680-688.

LISENBEE, W., HATHAWAY, J. & WINSTON, R. 2022. Modeling bioretention hydrology: Quantifying the performance of DRAINMOD-Urban and the SWMM LID module. *Journal of Hydrology,* 612**,** 128179.

LIU, J., SAMPLE, D. J., BELL, C. & GUAN, Y. 2014. Review and research needs of bioretention used for the treatment of urban stormwater. *Water,* 6**,** 1069-1099.

LIU, R. & FASSMAN-BECK, E. 2017. Hydrologic experiments and modeling of two laboratory bioretention systems under different boundary conditions. *Frontiers of Environmental Science & Engineering,* 11**,** 1-10.

LIU, Y., AHIABLAME, L. M., BRALTS, V. F. & ENGEL, B. A. 2015. Enhancing a rainfall-runoff model to assess the impacts of BMPs and LID practices on storm runoff. *Journal of environmental management,* 147**,** 12-23.

MCCUEN, R. H. 1989. *Hydrologic analysis and design*, Prentice-Hall Englewood Cliffs, NJ.

MOHSEN, K. A., NILE, B. K. & HASSAN, W. H. Experimental work on improving the efficiency of storm networks using a new galley design filter bucket. IOP Conference Series: Materials Science and Engineering, 2020. IOP Publishing, 012094.

MOVAHEDINIA, M., SAMANI, J. M. V., BARAKHASI, F., TAGHVAEIAN, S. & STEPANIAN, R. 2019. Simulating the effects of low impact development approaches on urban flooding: a case study from Tehran, Iran. *Water Science and Technology,* 80**,** 1591-1600.

NELSON, E. J. & BOOTH, D. B. 2002. Sediment sources in an urbanizing, mixed land-use watershed. *Journal of Hydrology,* 264**,** 51-68.

NELSON, K. C. & PALMER, M. A. 2007. Stream temperature surges under urbanization and climate change: data, models, and responses 1. *JAWRA journal of the American water resources association,* 43**,** 440-452.

NHAT, L. M., TACHIKAWA, Y. & TAKARA, K. 2006. Establishment of intensity-duration-frequency curves for precipitation in the monsoon area of Vietnam. *Annuals of Disas. Prev. Res. Inst,* 49**,** 93-103.

NIU, Z.-G., CHEN, Y.-X., MI, Z.-M., LI, P., GUO, L.-Y. & LI, Z.-H. 2012. Simulation of rainwater landscape use in eco-town based on SWMM and WASP models. *China Water & Wastewater,* 28**,** 50-52.

OBAID, H., SHAMSUDDIN, S., BASIM, K. & SHREESHIVADASAN, C. 2014. Modeling sewer overflow of a city with a large floating population. *Hydrology: current research,* 5**,** 1.

OGUNRINDE, A. T., OGUNTUNDE, P. G., OLASEHINDE, D. A., FASINMIRIN, J. T. & AKINWUMIJU, A. S. 2020. Drought spatiotemporal characterization using self-calibrating Palmer Drought Severity Index in the northern region of Nigeria. *Results in Engineering,* 5**,** 100088.

OSTROFF, G. M. 2005. A micro & macro-model approach to evaluating greenroofs as a CSO control in New York City. *Impacts of global climate change.*

PACHAURI, R. K., ALLEN, M. R., BARROS, V. R., BROOME, J., CRAMER, W., CHRIST, R., CHURCH, J. A., CLARKE, L., DAHE, Q. & DASGUPTA, P. 2014. *Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change*, Ipcc.

PANOS, C. L., HOGUE, T. S., GILLIOM, R. L. & MCCRAY, J. E. 2018. High-resolution modeling of infill development impact on stormwater dynamics in Denver, Colorado. *Journal of Sustainable Water in the Built Environment,* 4**,** 04018009.

POMEROY, C., POSTEL, N., O'NEILL, P. & ROESNER, L. 2008. Development of storm-water management design criteria to maintain geomorphic stability in Kansas City metropolitan area streams. *Journal of irrigation and drainage engineering,* 134**,** 562-566.

POUYAT, R. V., YESILONIS, I. D., RUSSELL-ANELLI, J. & NEERCHAL, N. K. 2007. Soil chemical and physical properties that differentiate urban land-use and cover types. *Soil Science Society of America Journal,* 71**,** 1010-1019.

PREVENTION, P. 2005. National management measures to control nonpoint source pollution from urban areas. *Environmental Protection Agency, Cincinnati*.

RABORI, A. M. & GHAZAVI, R. 2018. Urban flood estimation and evaluation of the performance of an urban drainage system in a semi-arid urban area using SWMM. *Water Environment Research,* 90**,** 2075-2082.

RANGARI, V. A., PRASHANTH, S. S., UMAMAHESH, N. & PATEL, A. K. 2018. Simulation of urban drainage system using a storm water

management model (SWMM). *Asian Journal of Engineering and Applied Technology,* 7**,** 7-10.
RASEL, M. M. & ISLAM, M. M. 2015. Generation of rainfall intensity-duration-frequency relationship for North-Western Region in Bangladesh. *IOSR Journal of Environmental Science, Toxicology and Food Technology,* 9**,** 41-47.
RAWLS, W. J., BRAKENSIEK, D. L. & MILLER, N. 1983. Green-Ampt infiltration parameters from soils data. *Journal of hydraulic engineering,* 109**,** 62-70.
REZAEI, A. R., ISMAIL, Z., NIKSOKHAN, M. H., DAYARIAN, M. A., RAMLI, A. H. & SHIRAZI, S. M. 2019. A quantity–quality model to assess the effects of source control stormwater management on hydrology and water quality at the catchment scale. *Water,* 11**,** 1415.
ROSSMAN, L. 2010. Storm Water Management Model User's Manual Version 5.0. *US Environmental Protection Agency*.
ROSSMAN, L. A. & HUBER, W. C. 2016a. Storm water management model reference manual volume I–Hydrology. *US Environmental Protection Agency,* 3.
ROSSMAN, L. A. & HUBER, W. C. 2016b. Storm water management model reference manual volume III–water quality. *US Environmental Protection Agency: Cincinnati, OH, USA*.
SALERNO, F., GAETANO, V. & GIANNI, T. 2018. Urbanization and climate change impacts on surface water quality: Enhancing the resilience by reducing impervious surfaces. *Water research,* 144**,** 491-502.
SAUER, E. P., VANDEWALLE, J. L., BOOTSMA, M. J. & MCLELLAN, S. L. 2011. Detection of the human specific Bacteroides genetic marker provides evidence of widespread sewage contamination of stormwater in the urban environment. *Water research,* 45**,** 4081-4091.
SELVALINGAM, S., LIONG, S. & MANOHARAN, P. 1987. Use of RORB and SWMM models to an urban catchment in Singapore. *Advances in water Resources,* 10**,** 78-86.
SENEVIRATNE, S., NICHOLLS, N., EASTERLING, D., GOODESS, C., KANAE, S., KOSSIN, J., LUO, Y., MARENGO, J., MCINNES, K. & RAHIMI, M. cc Author (s) 2019. *CC BY,* 4.
SERCU, B., VAN DE WERFHORST, L. C., MURRAY, J. L. & HOLDEN, P. A. 2011. Sewage exfiltration as a source of storm drain contamination during dry weather in urban watersheds. *Environmental science & technology,* 45**,** 7151-7157.

SHAFIQUE, M. & KIM, R. 2015. Low impact development practices: a review of current research and recommendations for future directions. *Ecological Chemistry and Engineering S,* 22**,** 543-563.
SHAFIQUE, M., KIM, R. & KYUNG-HO, K. 2018. Rainfall runoff mitigation by retrofitted permeable pavement in an urban area. *Sustainability,* 10**,** 1231.
SHEN, J. & ZHANG, Q. 2014. Parameter estimation method for SWMM under the condition of incomplete information based on GIS and RS. *EJGE. Pp***,** 6095-6108.
SHENG, A. Energy, environment and green building materials. Proceedings of the International Conference on Energy, Environment and Green Building Materials, Guilin, Guangxi, China, 2014. 28-30.
SIROVA, V. 2015. Urban stormwater management: treatment of heavy metals and polycyclic aromatic hydrocarbons with bioretention and permeable pavement technologies.
STÅLNACKE, P. & GOOCH, G. D. 2010. Integrated water resources management. *Irrigation and Drainage Systems,* 24**,** 155-159.
SUN, Y. 2011. Eco-hydrological impacts of urbanization and low impact development. *Northwest A&F University: Xi'an, China*.
TANG, Y. 2010. Study of urban stormwater runoff BMPs Planning with support of SUSTAIN system. *School of Environment; Tsinghua University: Beijing, China*.
TIKKANEN, H. 2013. *Hydrological modeling of a large urban catchment using a stormwater management model (SWMM).* Aalto University.
VAN DER STERREN, M., RAHMAN, A. & RYAN, G. 2014. Modeling of a lot scale rainwater tank system in XP-SWMM: A case study in Western Sydney, Australia. *Journal of environmental management,* 141**,** 177-189.
VARIS, O. & SOMLYÓDY, L. 1997. Global urbanization and urban water: can sustainability be afforded? *Water Science and Technology,* 35**,** 21-32.
VILLARREAL, E. L., SEMADENI-DAVIES, A. & BENGTSSON, L. 2004. Inner city stormwater control using a combination of best management practices. *Ecological Engineering,* 22**,** 279-298.
VORREITER, L. & HICKEY, C. 1994. Incidence of the first flush phenomenon in catchments of the Sydney region. *Water Down Under 94: Surface Hydrology and Water Resources Papers; Preprints of Papers.* Institution of Engineers, Australia Barton, ACT.
WALTON, B. M., SALLING, M., WYLES, J. & WOLIN, J. 2007. Biological integrity in urban streams: Toward resolving multiple

dimensions of urbanization. *Landscape and Urban Planning,* 79**,** 110-123.
WANG, H.-Y., LIU, M., LIU, Q.-M. & HOU, L.-J. 2003. Analysis and Research Progress on Urban Rainfall Runoff Non-point Source Pollution. *Urban Environment & Urban Ecology,* 16**,** 283-285.
WANG, W.-L., LI, J.-Q., GONG, Y.-W., ZHU, M.-J. & ZHANG, Q.-K. 2012. LID stormwater control effect simulation based on SWMM. *China Water & Wastewater,* 28**,** 42-44.
WANG, Z., LIU, L. & SONG, L. 2008. Application of Mike21 in ecological design of artificial lake. *Water Resources and Power,* 26**,** 124-127.
WARD, E. & WINTER, K. 2016. Missing the link: urban stormwater quality and resident behaviour. *Water SA,* 42**,** 571-576.
WEN, T., STUCKE, E. M., GROTJAN, T. M., KEMME, K. A., ABONIA, J. P., PUTNAM, P. E., FRANCIOSI, J. P., GARZA, J. M., KAUL, A. & KING, E. C. 2013. Molecular diagnosis of eosinophilic esophagitis by gene expression profiling. *Gastroenterology,* 145**,** 1289-1299.
XU, H., RANDALL, M. & FRYD, O. 2023. Urban stormwater management at the meso-level: A review of trends, challenges and approaches. *Journal of Environmental Management,* 331**,** 117255.
YU-JIE, W. & XIN, L. 2022. A review of climate change and its impact and adaptation in Beijing-Tianjin-Hebei urban agglomeration. *Advances in Climate Change Research,* 18**,** 743.
ZAHMATKESH, Z., BURIAN, S. J., KARAMOUZ, M., TAVAKOL-DAVANI, H. & GOHARIAN, E. 2015. Low-impact development practices to mitigate climate change effects on urban stormwater runoff: Case study of New York City. *Journal of Irrigation and Drainage Engineering,* 141**,** 04014043.
ZENG, H., SONG, L., YU, Z. & CHEN, H. 2006. Distribution of phytoplankton in the Three-Gorge Reservoir during rainy and dry seasons. *Science of the Total Environment,* 367**,** 999-1009.
ZHANG, L., YE, Z. & SHIBATA, S. 2020. Assessment of rain garden effects for the management of urban storm runoff in Japan. *Sustainability,* 12**,** 9982.
ZHANG, W., MENG, Y. & XUE, L. 2023. Evaluating low impact development of Urban rainwater management at the watershed scale.
ZHAO, D., DONG, L., WANG, H. & XING, W. 2011. Global sensitivity analysis of a rainfall-runoff model using continuous simulation. *Acta Sci. Circumstantiae,* 31**,** 717-723.
ZHEN, J., CHENG, M.-S., RIVERSON, J., ALVI, K. & SARAVANAPAVAN, T. 2010. Comparison of BMP infiltration

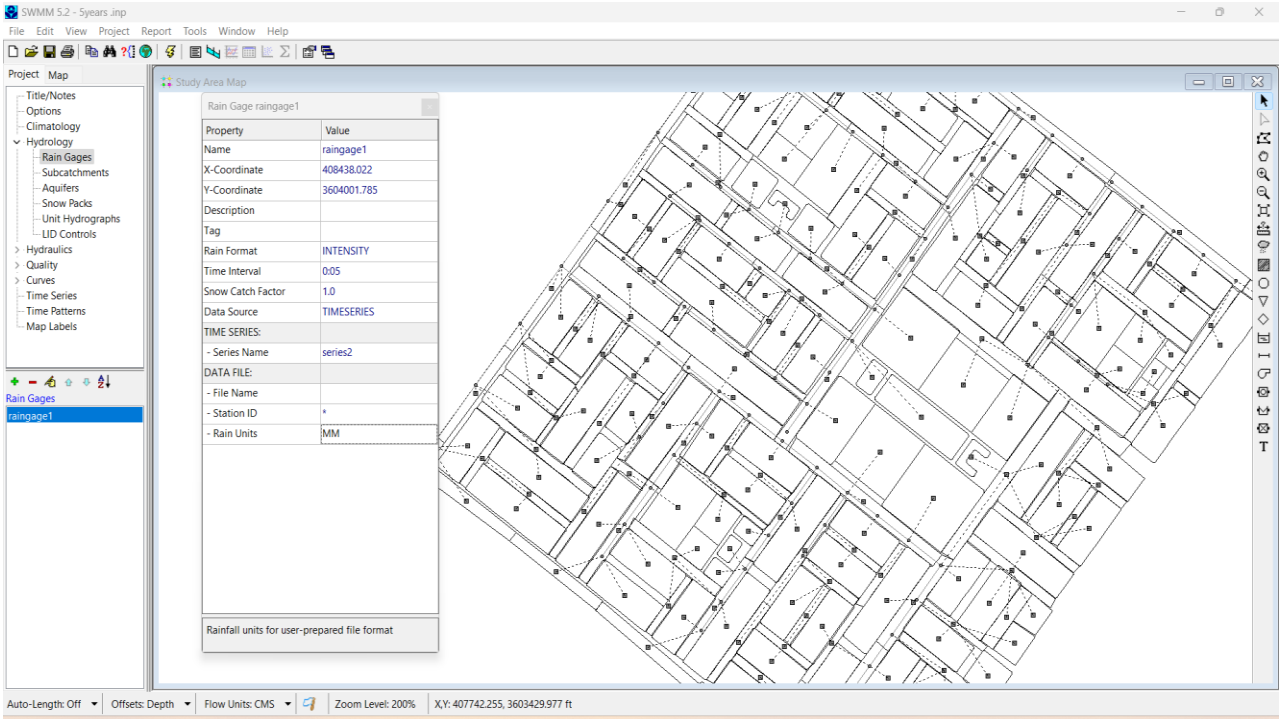
simulation methods. *Low Impact Development 2010: Redefining Water in the City*.

ZHEN, J., SHOEMAKER, L., RIVERSON, J., ALVI, K. & CHENG, M.-S. 2006. BMP analysis system for watershed-based stormwater management. *Journal of Environmental Science and Health, Part A,* 41**,** 1391-1403.

ZHEN, J. X. & YU, S. L. 2001. Development of a best management practice (BMP) placement strategy at the watershed scale. *Wetlands Engineering & River Restoration 2001*.

ZIMMER, C., HEATHCOTE, I., WHITELEY, H. & SCHROTER, H. 2007. Low-impact-development practices for stormwater: Implications for urban hydrology. *Canadian Water Resources Journal,* 32**,** 193-212.

Appendix

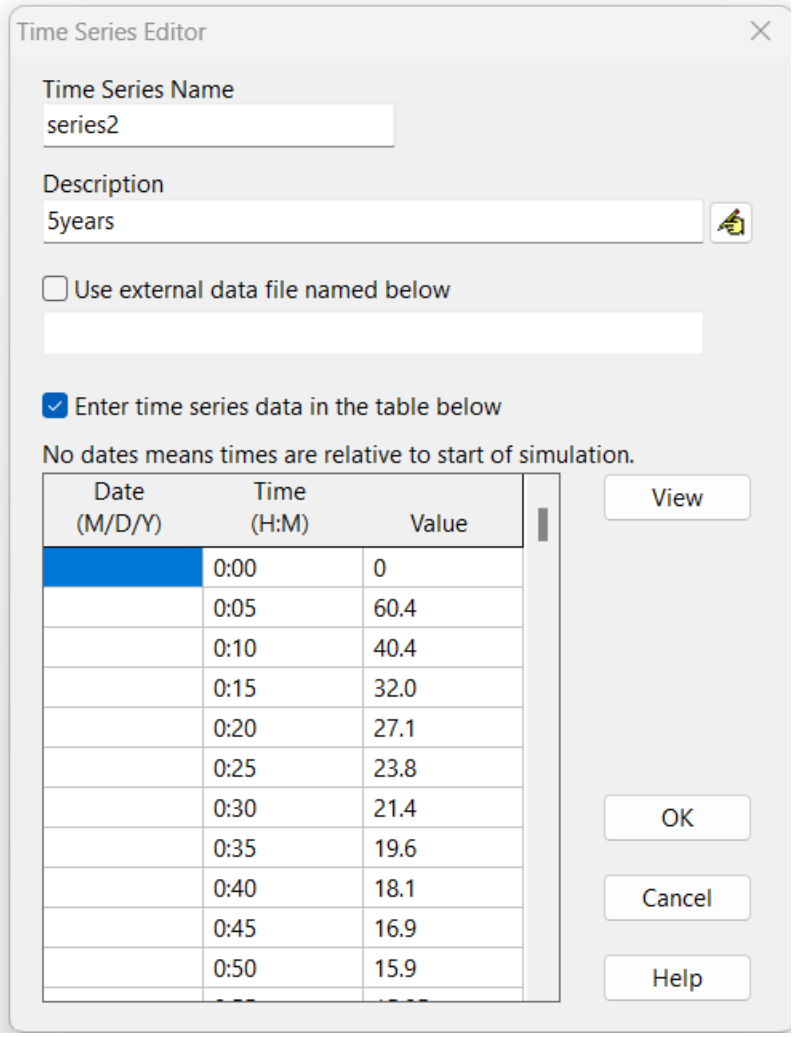


FigureA- 3 Software Interface for SWMM

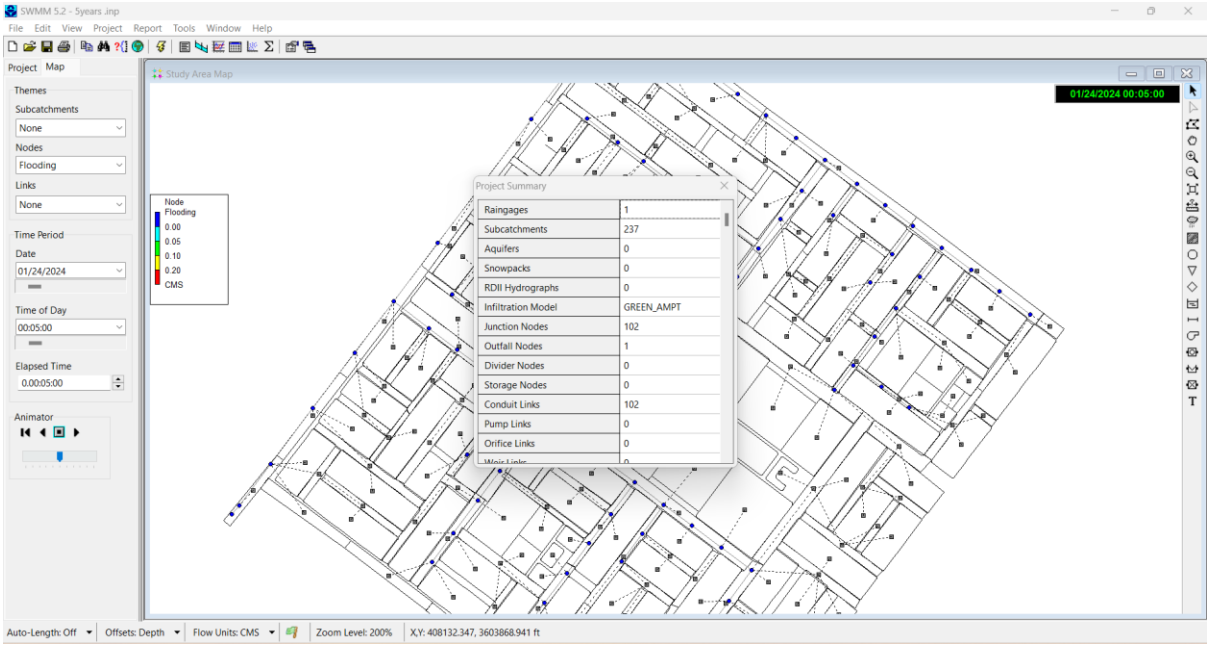
Return Period T (yr)				
	2	5	10	20
Duration (min.)				
2	68.9	102.7	125.2	146.7
2.5	60.5	90.3	110.0	128.9
3	54.5	81.2	99.0	116.0
3.5	49.8	74.3	90.5	106.0
4	46.1	68.8	83.8	98.2
4.5	43.1	64.2	78.2	91.7
5	40.5	60.4	73.6	86.3
5.5	38.3	57.2	69.7	81.6
6	36.5	54.4	66.2	77.6
6.5	34.8	51.9	63.2	74.1
7	33.3	49.7	60.6	71.0
7.5	32.0	47.8	58.2	68.2
8	30.9	46.0	56.1	65.7
8.5	29.8	44.4	54.1	63.4
9	28.8	43.0	52.4	61.4
9.5	27.9	41.7	50.8	59.5
10	27.1	40.4	49.3	57.7
10.5	26.4	39.3	47.9	56.1
11	25.7	38.3	46.6	54.6
11.5	25.0	37.3	45.4	53.2
12	24.4	36.4	44.3	51.9
12.5	23.8	35.5	43.3	50.7
13	23.3	34.7	42.3	49.6
13.5	22.8	34.0	41.4	48.5
14	22.3	33.3	40.5	47.5
14.5	21.9	32.6	39.7	46.5
15	21.4	32.0	39.0	45.6
15.5	21.0	31.4	38.2	44.8
16	20.7	30.8	37.5	44.0
16.5	20.3	30.3	36.9	43.2
17	19.9	29.7	36.2	42.5
17.5	19.6	29.2	35.6	41.7
18	19.3	28.8	35.0	41.1
18.5	19.0	28.3	34.5	40.4
19	18.7	27.9	34.0	39.8
19.5	18.4	27.5	33.5	39.2
20	18.2	27.1	33.0	38.6

Return Period T (yr)				
	2	5	10	20
Duration (min.)				
21	17.6	26.3	32.1	37.6
22	17.2	25.6	31.2	36.6
23	16.7	25.0	30.4	35.6
24	16.3	24.4	29.7	34.8
25	16.0	23.8	29.0	34.0
26	15.6	23.3	28.3	33.2
27	15.3	22.8	27.7	32.5
28	14.9	22.3	27.1	31.8
29	14.6	21.8	26.6	31.2
30	14.4	21.4	26.1	30.5
32	13.8	20.6	25.1	29.4
34	13.3	19.9	24.2	28.4
36	12.9	19.3	23.5	27.5
38	12.5	18.7	22.7	26.6
40	12.1	18.1	22.1	25.9
142	11.8	17.6	21.5	25.1
44	11.5	17.1	20.9	24.5
46	11.2	16.7	20.4	23.8
48	10.9	16.3	19.9	23.3
50	10.7	15.9	19.4	22.7
52	10.4	15.6	19.0	22.2
54	10.2	15.2	18.5	21.7
56	10.0	14.9	18.2	21.3
58	9.8	14.6	17.8	20.9
60	9.6	14.3	17.4	20.4
65	9.2	13.7	16.7	19.5
70	8.8	13.1	16.0	18.7
75	8.4	12.6	15.3	18.0
80	8.1	12.1	14.8	17.3
85	7.9	11.7	14.3	16.7
90	7.6	11.3	13.8	16.2
95	7.4	11.0	13.4	15.7
100	7.1	10.7	13.0	15.2
105	6.9	10.4	12.6	14.8
110	6.8	10.1	12.3	14.4
115	6.6	9.8	12.0	14.0
120	6.4	9.6	11.7	13.7

Figure A-2 Rain full intensities at various frequencies for Kerbala City, Iraq.



FigureA- 3 An editor for time series with a return period of 5 years.



FigureA- 4 Summary Project

Subcatchment Sub-123

Property	Value
Name	Sub-123
X-Coordinate	408477.792
Y-Coordinate	3603171.527
Description	
Tag	
Rain Gage	raingage1
Outlet	hr24
Area	0.082413
Width	139.896
% Slope	0.5000
% Imperv	25.00
N-Imperv	0.011
N-Perv	0.15
Dstore-Imperv	2.54
Dstore-Perv	5.08
%Zero-Imperv	25
Subarea Routing	OUTLET
Percent Routed	100
Infiltration Data	GREEN_AMPT
Groundwater	NO
Snow Pack	
LID Controls	1
Land Uses	0

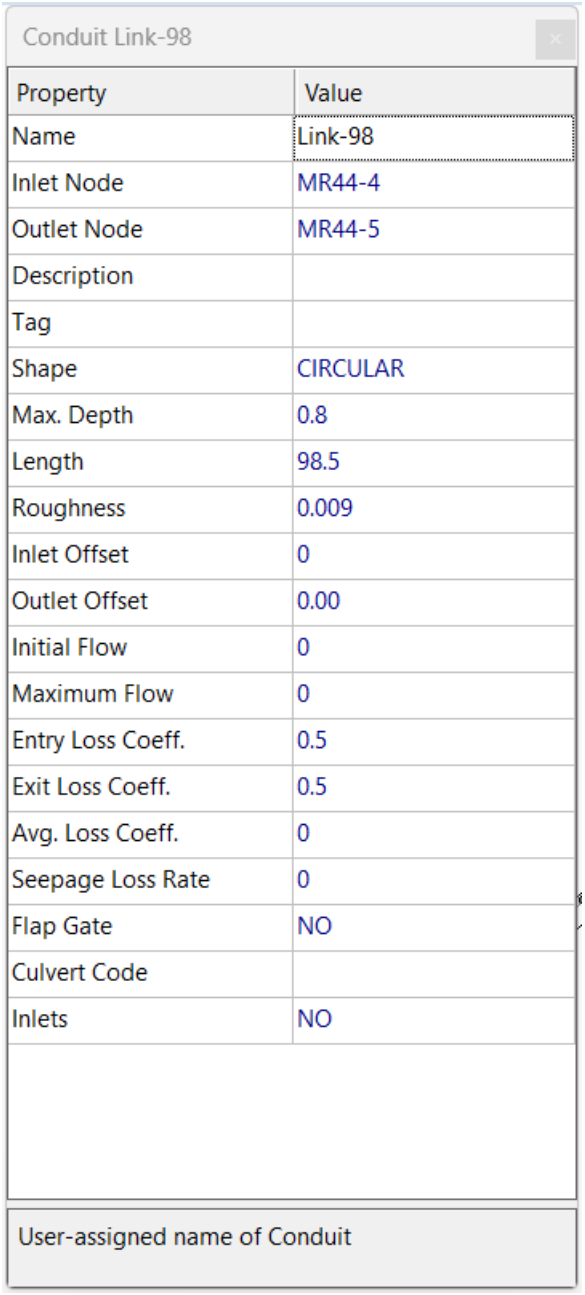
Depth of depression storage on pervious area (mm)

Junction MR44-4

Property	Value
Name	MR44-4
X-Coordinate	408153.440
Y-Coordinate	3603409.360
Description	
Tag	
Inflows	NO
Treatment	NO
Invert El.	35.16
Max. Depth	6.64
Initial Depth	0
Surcharge Depth	0
Ponded Area	0.00

User-assigned name of junction

Figure A- 5 The "Subcatchment and manholes Properties" input in SWMM



FigureA- 6 The "Pipes Properties" input in SWMM

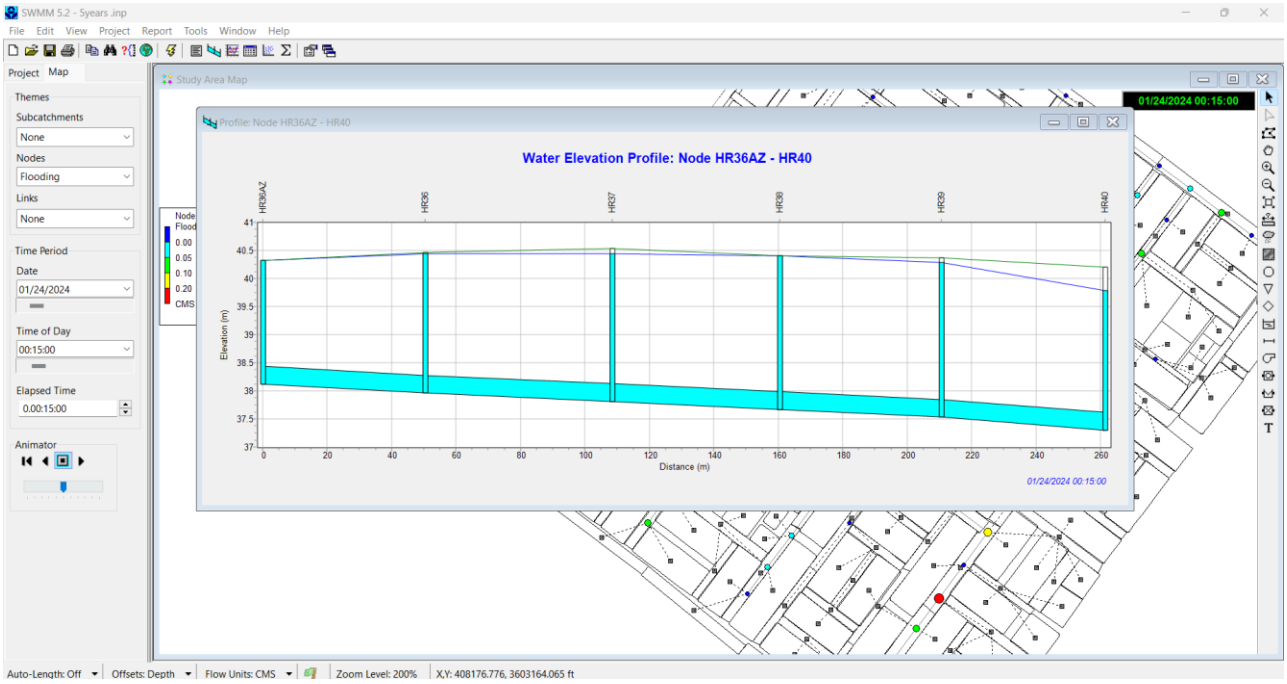


Figure A- 7 Water elevation profile: node (HR36AZ-HR40) during rainfall

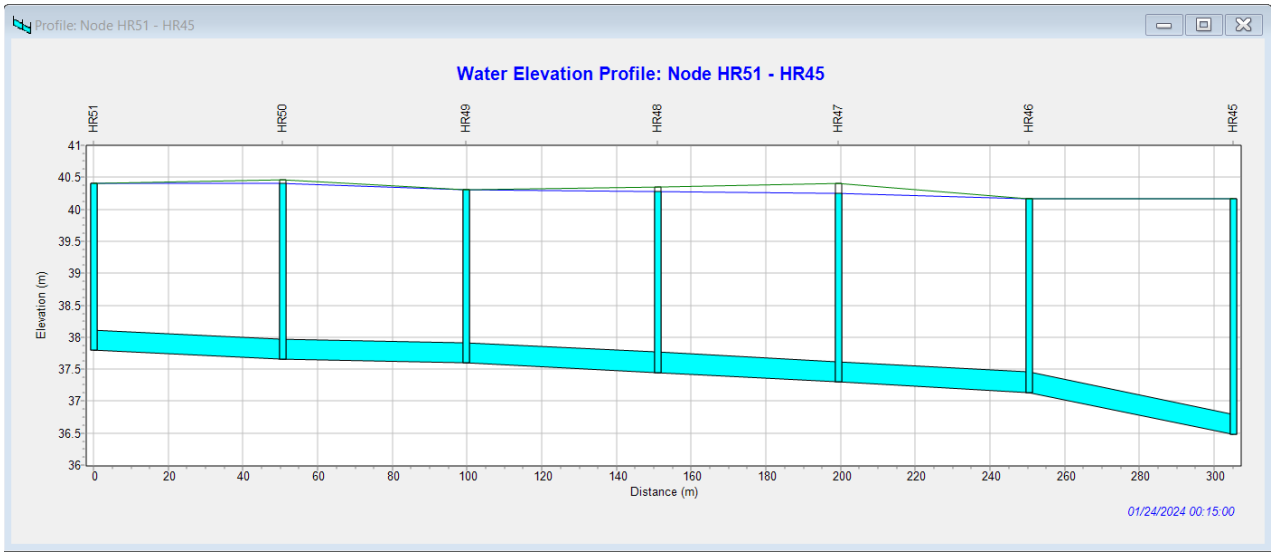


Figure A- 8 Water elevation profile: node (HR51-HR45) during rainfall

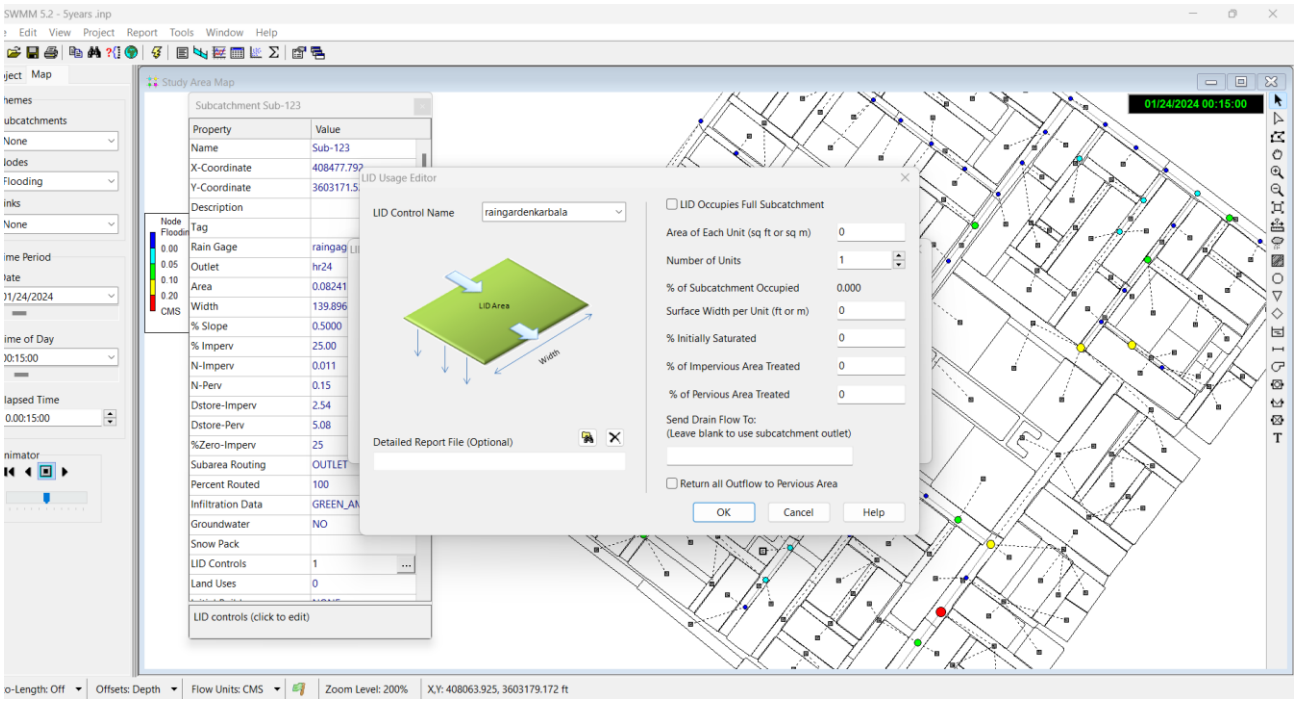


Figure A- 9 Enter the technical characteristics of the LID in the sum

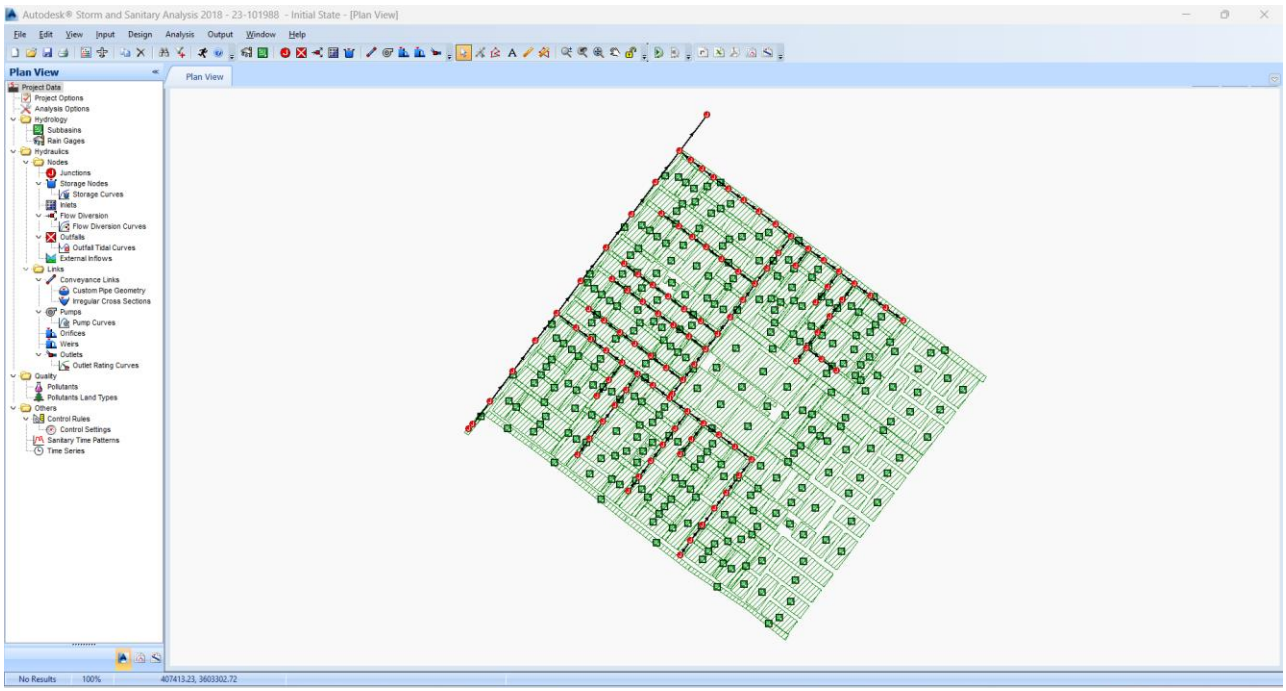


Figure A- 10 Modify the network direction in the software (SSA)

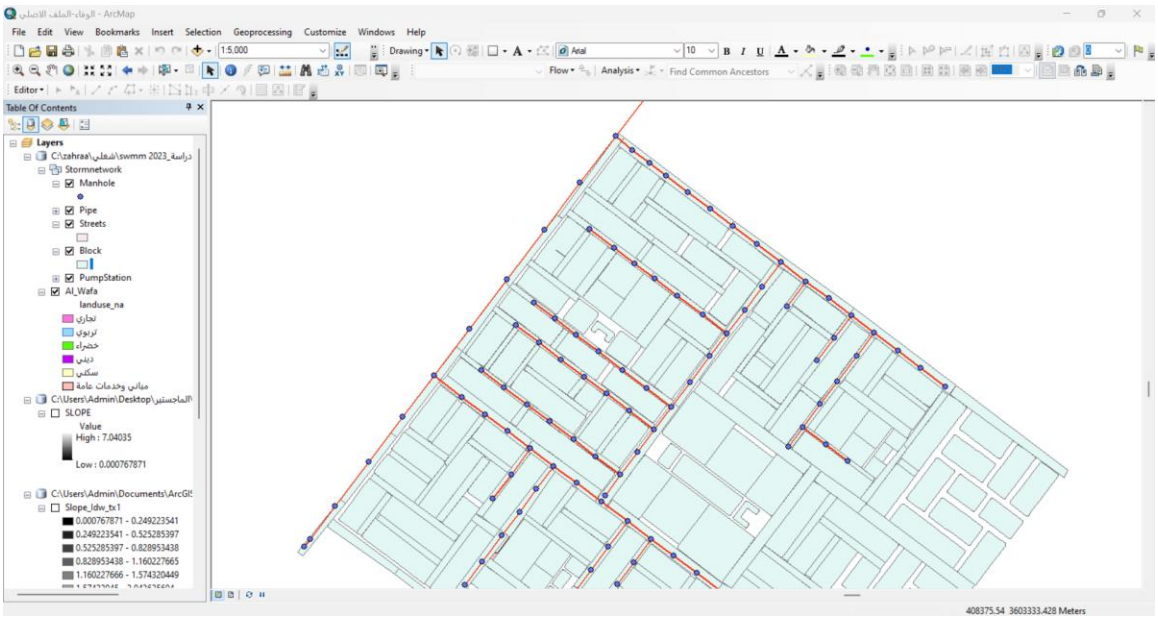


Figure A- 4 Drawing blocks in the software (GIS)

الخلاصة

تتأثر أنماط هطول الأمطار بتغير المناخ في المنطقة مما يؤدي إلى زيادة الجريان السطحي وبالتالي إغراق شبكة مياه الأمطار في الحي. وقد تبنت معظم المدن تدابير وأهداف إدارة مياه الأمطار المستدامة للحفاظ على الموارد المائية. أدت الظروف المناخية المتغيرة والتقلبات الموسمية إلى زيادة مستويات هطول الأمطار وتراكمها على الأرصفة والطرق وتجمعها داخل الطرق. تهدف هذه الدراسة إلى إيجاد طريقة حديثة للتحول من أساليب إدارة مياه الأمطار التقليدية إلى أساليب أكثر استدامة، بناءً على اختيار مدينة كربلاء في العراق، وبشكل أكثر دقة، حي الوفاء الواقع جنوب غرب المدينة، والاعتماد على جمع البيانات التاريخية (بيانات الأمطار والشبكة) لبناء نموذج محاكاة لشبكة مياه الأمطار في المنطقة باستخدام برنامج نموذج إدارة مياه الأمطار (SWMM) ودراسة تأثير الفيضانات على شبكة مياه الأمطار في حي الوفاء. تم تقييم فعالية شبكة مياه الأمطار في المنطقة قبل وبعد هطول الأمطار لعدة فترات تكرارية لمدة 2 و 5 و 10 و 20 عامًا. كما تم معايرة النموذج بعد تحليله بتعديل خصائص الأحواض الفرعية الهامة التي تم حسابها بناء على التصريفات النمذجية والمرصودة، وقد بلغ حجم الفيضان في الشبكة بعد التحليل 6921م^3 في فترة العودة 2 سنة ثم ارتفع إلى 9956م^3 عند تمديد فترة العودة إلى 20 سنة، وذلك بسبب تغير المناخ وبالتالي أدى إلى حدوث فيضانات في شبكة مياه الأمطار في المناطق المجاورة مما يؤثر سلبا على البنية التحتية للشبكة، وقد تم تحديد مواقع الفيضانات في الشبكة من خلال البرنامج واقتراح الحلول المناسبة لهذه المشكلة مع الحفاظ على قيمة خطأ متوسط المربعات الطبيعي (NMSE) الذي بلغ 1.16 في فترة العودة 2 سنة ومعامل التحديد 0.934 (R^2)، أما في فترة العودة 20 سنة فقد بلغ خطأ متوسط المربعات الطبيعي 0.93 (NMSE) ومعامل التحديد 0.899 (R^2) ضمن الحدود المقبولة. تم اقتراح ثلاثة خطوط تصريف إضافية للشبكة، وتم إضافة تقنية LID لتحقيق الاستدامة، مما أدى إلى انخفاض وتيرة الفيضانات. تعد حدائق الأمطار من الطرق الأساسية للسيطرة الكاملة على جريان المياه السطحية أثناء الفيضانات. كما تم تطبيق هذه الطريقة في منطقة كربلاء الوفاء للسيطرة على الفيضانات الأولية الناجمة عن شبكة مياه الأمطار. تم التأكد من الحد الأقصى للتصريف من خلال محاكاة المنطقة قبل وبعد إضافة حدائق الأمطار. بعد المحاكاة، كان انخفاض الفيضانات 10.47٪، 19.4٪، 15.99٪، و 15.46٪ على مدى فترات العودة 2 و 5 و 10 و 20 عامًا على التوالي. أظهرت النتائج فرقًا واضحًا في تقليل الفيضانات. لوحظ أن الحد الأقصى لعدد فتحات الصرف المغمورة خلال فترة العودة لمدة عامين كان 31 فتحة بدون حدائق مطرية، بينما بعد إضافة حدائق الأمطار انخفض العدد إلى 14 فتحة. وهذا يوضح فعالية حدائق الأمطار في الحد من الفيضانات.

جمهورية العراق

وزارة التعليم العالي و البحث العلمي

جامعة كربلاء

كلية الهندسة

قسم الهندسة المدنية

محاكاة شبكة الامطار باستخدام برنامج EPA SWMM في منطقة مستجمعات المياه غير الحضرية في مدينة كربلاء

رسالة مقدمة الى مجلس كلية الهندسة / جامعة كربلاء وهي جزء من متطلبات نيل درجة الماجستير في علوم الهندسة المدنية

المؤلف:

زهراء صبري وحيد

بكلوريوس في الهندسة المدنية /جامعة كربلاء (2013)

باشراف :

أ.م.د حيدر حسين علوان

أ.د. واقد حميد حسن

شعبان - 1446 يناير - 2025