Co-funded by the
Erasmus+ Programme
of the European Union

Green Roof Runoff Modelling in Dublin for Climate Resilience

Runoff Reduction Performance of a Single Green Roof for Stormwater Management Using Hydrological Modelling with Climate Change Projections

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A thesis submitted for the Joint programme of

Master in Urban Climate & Sustainability

August 2021

Author Last = Ozkan, First = Asiye Irmak	**Publication type** Thesis	**Completion year** 2021
	Number of pages: 76	
Supervisor I Prof. Slobodan Mickovski,	**Supervisor II** Dr. Bidroha Basu	

Title

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Degree: Master in Urban Climate & Sustainability

Abstract (400-500 words)

This thesis aims to show the runoff reduction performance of green roofs based on climate change projection scenarios using hydrological simulation tools for mitigating and adapting to flooding events in a flood prone city, Dublin.

Green roofs like other sustainable urban drainage systems are able to reduce and delay runoff but the reduction performance depend on many design features as well as external factors. Simulation methods can be used to tailor and enhance the design of green roofs to create a more sustainable urban drainage system while adapting future weather conditions that depend on climate change and mitigate the risk of flooding. Currently, hydrological simulation methods are more frequently used to assess the design, deployment and the impact of sustainable drainage solutions but more studies are needed that includes that are based on simulations validated with real life data and climate change projection models. This study is based on a model validated with real life data and uses climate change projetion model to assess the future implications of climate change and the impact of a green roof could have in stormwater management in Dublin. The model is created using Soil and Water Assessment Tool (SWAT) and calibrated according to a green roof deployed in Dublin based on observed runoff from the green roof. The model is later used with weather parameters taken from a climate change projection model. The runoff obtained from this model is bias corrected using the runoff from the model that uses the historical weather parameters. A further analysis of the urbanization trends of Dublin which will affect the future of the city and its stormwater management strategies and flooding problems. The runoff reduction is assessed compared to the foreseen changes in the land use of the city.

Main findings show the green roof is able to reduce %26-%55 of the runoff while the performance drops in more frequent and intense rain events. It is observed that climate change models are subjected to significant biases for weather parameters, especially for precipitation and bias correction on input variables or outputs is strongly advised. The urbanization trend shows Dublin, like many other cities will be more impervious in the future which will add to the effects of climate change. Multiple green roofs together with other sustainable drainage systems can create a cascading effect on overall runoff of the city, alleviating risk of flooding.

Keywords

Green roof, runoff reduction, stormwater management, modelling, SWAT, climate change projection, Dublin, flooding, sustainable urban drainage systems

Originality statement. I hereby declare that this Master's dissertation is my own original work, does not contain other people's work without this being stated, cited and referenced, has not been submitted elsewhere in fulfilment of the requirements of this or any other award.	**Signature**

TABLE OF CONTENTS

ACKNOWLEDGEMENT 3

LIST OF FIGURES 5

LIST OF TABLES 7

ABBREVIATIONS 9

CHAPTER 1 INTRODUCTION 11

- 1.1. Rationale 11
- 1.2. Research Aim and Objectives 12
- 1.3. Methods 13
- 1.4. Thesis Structure 14

CHAPTER 2 LITERATURE REVIEW 15

- 2.1. Green Roofs in stormwater management 15
- 2.2. Green Roof Design 15
  - 2.2.1. Types of Green Roofs 15
  - 2.2.1.1. Extensive Green Roofs 16
  - 2.2.1.2. Intensive Green Roofs 16
  - 2.2.1.3. Semi-Intensive Green Roofs 17
  - 2.2.2. Properties and Maintenance of Green Roofs 17
  - 2.2.2.1. Imposed Load of Green Roofs for Buildings 18
  - 2.2.2.2. Waterproofing Green Roofs 18
  - 2.2.2.3. Drainage system 19
  - 2.2.2.4. Growing Medium / Substrate 19
  - 2.2.2.5. Vegetation 19
  - 2.2.2.6. Green roof maintenance 20
- 2.3. Hydrological Performance of Green Roofs 20
  - 2.3.1. Hydraulic Performance Based on Green roof Type and Design 22
  - 2.3.2. Hydraulic Performance Based on Vegetation 22
  - 2.3.3. Hydraulic Performance Based on Climate Conditions 23
- 2.4. Policies for green roofs 23
- 2.5. Climate Change and Urbanization Implications for Dublin 28

CHAPTER 3 METHODOLOGY 31

- 3.1. Green Roof Setup 31

3.2. Modelling Methods 32
3.3. Simulation setup 33
3.4. Data Collection 33
3.5. Model Setup to Evaluate Green Roof Performance 35
3.6. Model Validation 37
3.7. Simulation for Climate Change Projection Data 38
3.8. Bias Correction 39
3.9. Urbanization trend analysis for Dublin 41
CHAPTER 4 RESULTS AND DISCUSSION 43
4.1. Green Roof Performance under Current Meteorological Conditions 43
4.2. Analysis of the Data 43
4.3. Model Validation Results 46
4.4. Green Roof Performance with Observed Data 47
4.5. Green Roof Performance with Climate Change Projection 49
4.6. Analysis of the Data 49
4.7. Scenario RCP 4.5 51
4.8. Scenario RCP 8.5 53
4.9. Effects of Bias Correction 54
4.10. Potential for Sustainable Stormwater Management 56
4.11. LULC Changes in Dublin 57
CHAPTER 5 CONCLUSIONS 65
REFERENCES 69

ACKNOWLEDGEMENT

The research presented in this work was carried out as part of the MUrCS Erasmus Mundus Joint Master in Urban Climate and Sustainability program and it is based on the research of Dr. Bidroha Basu, Assistant Lecturer, Munster Technological University, Cork; Adjunct Assistant Professor, Trinity College Dublin; Research Fellow and Teaching Fellow, University College Dublin. So I would like to thank Dr. Basu for his support and wisdom during the development of this study. I would like to also thank you for my thesis supervisor Prof. Slobodan Mickovski for his guidance and comments for the preparation of this manuscript.

I am also grateful for my fellow MUrCSians for giving me constant inspiration with their brilliant minds, especially, my fellow MUrCS friend, Roberto Stohmann who was working on sustainable urban drainage systems as well for inspirational, thought-provoking, sometimes relaxing and sometimes nerve-wrecking discussions.

A very special thank you for my MUrCS professors, Prof. Rohinton Emmanuel, Prof. Eeva Aarrevaara and Dr José Antonio Dueñas Díaz for allowing me to follow my interests as well as Anne Bowman and Alexandra Maksheeva for their support throughout my degree.

Some special words of gratitude go to my friends: Ebru, Senem, Nadin, Melis. Thank you for being there for me.

A last word of thanks goes for my family, Muazzez, Rustu, Deniz, Kaan, Ekin Serdar, who always believed in me and my love Ibrahim for his unconditional support and encouragement.

LIST OF FIGURES

FIGURE 1 AIM AND OBJECTIVES 13
FIGURE 2 TYPICAL STRUCTURE OF A GREEN ROOF 18
FIGURE 3 MODULAR GREEN ROOF TRAY 31
FIGURE 4 WEATHER STATION AND RAIN GAUGE 32
FIGURE 5 LOCATION OF THE DUBLIN AIRPORT WEATHER STATION AND THE GREEN ROOF SITE . 34
FIGURE 6 FLOWCHART OF THE SIMULATION MODEL TO ESTIMATE THE DAILY RUNOFF FROM THE GREEN ROOF 36
FIGURE 7 EIGHT MODELLED CASES FOR THE CURRENT DAY RUNOFF PERFORMANCE MODELLING 37
FIGURE 8 VISUALISATION OF THE BIAS CORRECTION METHOD (LI ET AL., 2010) 40
FIGURE 9 THE RELIABILITY OF THE MODEL RESULTS (NUMBER OF CLIMATE SCENARIOS IN THE ENSEMBLE THAT SHOW AN INCREASE FOR THE PERIOD 2071-2100 COMPARED TO THE CONTROL PERIOD 1971-2000) 41
FIGURE 10 NEURAL NETWORK LEARNING CURVE FOR MLP-ANN ANALYSIS IN MOLUSCE . 42
FIGURE 11 HOURLY AND DAILY TIME SERIES PLOTS OF PRECIPITATION, TEMPERATURE, RELATIVE HUMIDITY AND MEAN WIND SPEED 44
FIGURE 12 HOURLY AND DAILY TIME SERIES PLOTS OF PRECIPITATION, TEMPERATURE, RELATIVE HUMIDITY AND MEAN WIND SPEED 45
FIGURE 13 MASS OF THE VEGETATED BED IN GRAMS (TOP), COMPARISON BETWEEN THE ACTUAL RUNOFF FROM THE VEGETATED BED AND THE SIMULATED RUNOFF (BOTTOM) 46
FIGURE 14 RUNOFF WITH AND WITHOUT THE GREEN ROOF 49
FIGURE 15 PRECIPITATION IN RCP4.5 BETWEEN 01/01/1981 AND 31/12/2100 50
FIGURE 16 PRECIPITATION IN RCP8.5 BETWEEN 01/01/1981 AND 31/12/2100 50
FIGURE 17 RUNOFF WITH AND WITHOUT THE GREEN ROOF IN RCP4.5 SCENARIO 52
FIGURE 18 RUNOFF WITH AND WITHOUT THE GREEN ROOF IN RCP8.5 SCENARIO 54
FIGURE 19 RUNOFF WITH AND WITHOUT GREEN ROOF WITH INTENSITY GREATER THAN 10MM WITH BIAS CORRECTION (LEFT) WITHOUT BIAS CORRECTION (RIGHT) 55
FIGURE 20 CDF GRAPH OF THE OBSERVED (BLACK) AND MODELLED (RED) RUNOFF 56
FIGURE 21 LAND USE CLASSES 58
FIGURE 22 LAND USE MAPS FOR 2006 AND 2018 58
FIGURE 23 LAND USE DISTRIBUTION IN 2006 59
FIGURE 24 LAND USE DISTRIBUTION IN 2018 60
FIGURE 25 LULC CHANGES BETWEEN 2006 AND 2018 62
FIGURE 26 BUILDINGS IN DUBLIN 64

LIST OF TABLES

TABLE 1 TRADITIONAL GREEN ROOF TYPOLOGIES (CREATED BY PEREZ ET AL., 2018 17
TABLE 2 GREEN ROOF RUNOFF REDUCTION RATES FROM LITERATURE (MODIFIED FROM SHAFIQUE ET AL., 2018)..........21
TABLE 3 INTERNATIONAL POLICIES CONCERNING GREEN ROOFS (MODIFIED FROM DONG ET AL., 2020; IRGA ET AL., 2017; GARY ET AL., 2019)..........25
TABLE 4 LITERATURE SUMMARY ON GREEN ROOF RUNOFF MODELLING 32
TABLE 5 RAINFALL INTENSITY DISTRIBUTION BETWEEN 01/01/1990 AND 29/02/2020 43
TABLE 6 RUNOFF REDUCTION RATE WITH A GREEN ROOF WITH DIFFERENT SUBSTRATE DEPTH AND VEGETATION UNDER OBSERVED HISTORICAL CLIMATE CONDITIONS..........47
TABLE 7 RAINFALL INTENSITY DISTRIBUTION BETWEEN 01/01/1990 AND 29/02/2020 50
TABLE 8 RUNOFF REDUCTION WITH GREEN ROOF IN RCP4.5 SCENARIO 51
TABLE 9 RUNOFF REDUCTION WITH GREEN ROOF IN RCP8.5 SCENARIO 53
TABLE 10 LAND USE CHANGE STATISTICS 61

ABBREVIATIONS

CDF Cumulative Distribution Function

EDCDFm Equidistant CDF Matching Method

ESGF Earth System Grid Foundation

GCM Global Climate Model

GHG Greenhouse Gas

GIS Geographic Information System

IPCC Intergovernmental Panel on Climate Change

QDM Quantile Delta Mapping

QM Quantile Mapping

RCM Regional Climate Model

RCP Representative Concentration Pathway

SMHI Meteorological and Hydrological Institute

SRES Special Report on Emission Scenarios

SWAT Soil and Water Assessment Tool

UN United Nations

CHAPTER 1 INTRODUCTION

1.1. RATIONALE

Climate change and urbanization are two drivers shaping the view towards city development. The observed land surface air temperature has risen by 1.53 °C since the industrialization which leads to extreme weather events like heatwaves and heavy precipitation (IPCC, 2019). Liu et al. suggested the rainfall events will increase 7% per degree of warming so, IPCC (Intergovernmental Panel on Climate Change) anticipates an increase in the frequency of flash floods, heavy precipitation, and extreme sea levels (IPCC, 2019). In addition, these changes are identified as anthropogenic and very likely to continue in this century (IPCC, 2013; Hoegh-Guldberg et al. 2018). It is also noteworthy to mention not only heavy precipitation but a combination of low to moderate precipitation for a long period often leads to serious environmental, social and economic impacts (Leonard et al. 2014).

IPCC states approximately a quarter of the Earth's accessible lands are deteriorated due to anthropological reasons (IPCC, 2019). Cities which are part of this deterioration, are growing fast as UN predicted almost 70% of the world's population will be living in cities by 2050 (UN, 2018). Already great numbers are living together in conventionally built cities where integrated environmental, social and economic issues arise, loss of natural cycles with increasing built-up area being one of them (Haase et al., 2014).

Built-up area in a conventional sense means impervious land cover which tears the natural hydrological cycle where rainfall run off loses its ability to infiltrate and balance the groundwater supply and quality (Shafique, 2018). Run off from impervious surfaces accumulate and may cause flash flooding or become a body of water that needs to be treated and discharged elsewhere. Thus, the water is lost to the local hydrological cycle and to any reuse options favouring resource efficiency. Scholz showed the stark difference between the surface run off from cities and forested areas which are 75% and 5%, respectively (Scholz-Barth, 2001). Traffic related land and rooftops are main impervious covers in cities whereof rooftops claim 30 to 50% (Mentens et al., 2006; Stovin et al., 2012). Increasing impervious built surfaces and increasing precipitation in some regions will double the severed hydrological cycle problem in cities. Furthermore, 40% of the future built areas in cities will be already been built by 2030 so, sustainable urban drainage solutions covering new developments and retrofitting conventional built areas, that include green roofs to win their imperviousness back to serve hydrological cycle come into play to tackle run off problem (SCBD, 2012).

Currently the most common stormwater management infrastructure is grey infrastructure that relies on drainage systems. The capacity of the urban drainage system is exceeded, or the system faces blockages relatively frequently which leads to urban flooding (Wheater et al., 2009). Grey infrastructure capacity increase through augmentation and duplication is common to alleviate urban flooding (Chocat et al., 2001). These solutions require high capital and operational investments and social disruption during their construction.

There are many studies on the usage of grey solutions can be optimized for better resilience to flooding and the effects of climate change (Balsells et al. 2015: Jia et al. 2012). Many conclude that in extreme storm events, the grey systems including pipes, underground retention basins and infiltration structures fail to discharge or remove the runoff when the annual recurrence interval is exceeded, by either degrading the pipe network and reducing the network robustness and resilience and through reaching the maximum retention capacity of underground basins (Valizadeh et al., 2019).

Gallo studied the trade-offs between green and grey infrastructure for stormwater management and found that grey solutions perform worst among the green infrastructure alternatives in terms of quantity of water retained the quality of discharged run off except for the required storage volume (Gallo et al., 2020). Gallo shows green infrastructure offers a wider range of benefits while grey infrastructure may outperform in terms of hydrological performance in some cases, depending on their design optimization. She also notes green solutions have a lower cost compared to grey per unit area but since the green infrastructure require more area to perform intended hydrological benefit, their overall cost may be higher. However, the green solutions also have beneficial properties as they enhance urban green areas and create the trade-offs between green and grey stormwater solutions. A combination of both could achieve more sustainable and improved hydrologic control for the environment and societies (Gallo et al., 2020).

1.2. RESEARCH AIM AND OBJECTIVES

Considering the benefits and trade-offs in favour of green stormwater solutions, more case studies should be conducted to understand and streamline the incorporation of green solutions to the modern stormwater management systems.

This study aims to show the impact of green roofs in a flood prone city, Dublin, on stormwater management and resilience to flooding using simulation techniques. Hydrological performance of a real green roof in terms of runoff reduction is recorded to be used building a simulation model to examine the runoff reduction that can be achieved with the green roof in the future where climate change scenarios might change weather conditions drastically. Model simulations developed and validated according to the real runoff and meteorological data are produced to observe the impact of the green roof on runoff by comparisons with and without the green roof deployment in the study area. Finally, future runoff models are developed with different climate change scenarios to observe the impact of the green roof in the study area under the implications of climate change. Figure 1 visualizes the aim and objectives of this study.

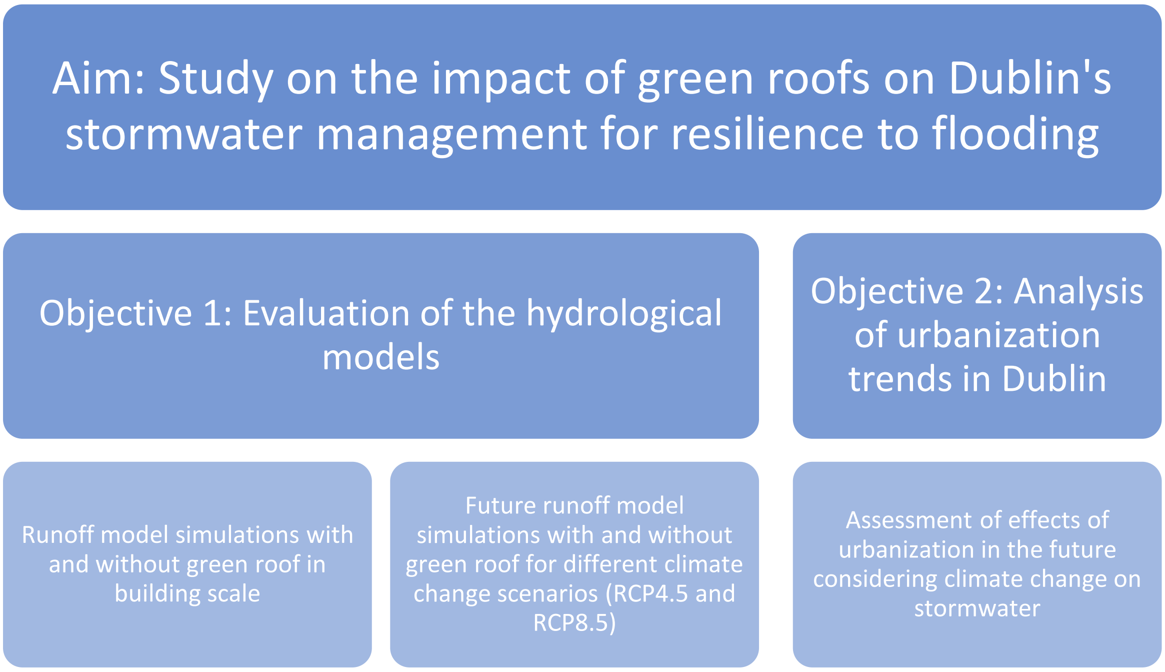


FIGURE 1 AIM AND OBJECTIVES

1.3. METHODS

The methodology builds upon the previous work undertaken by Bidroha Basu in Dublin based on an existing green roof in Dublin, deployed in February 2021, formed by 4 modular extensive roofs with a total area of 70 m^2. This real life setup, helps to validate the simulation model and assess its accuracy. The first objective of evaluation of hydrological model outcomes serves to understand the green roofs behaviour under different climatic conditions and rainfall events with different design configurations. The simulation is developed using Soil and Water Assessment Tool (SWAT) for first, the observed weather for a historical time period; second, for the projected historical and future data under two different climate change scenarios, RCP4.5 and RCP8.5 (Representative Concentration Pathway – RCP). This way the impact of the green roof run off is observed in line with climate change implications. The analysis is conducted in a building scale. In addition, the second objective is achieved through a GIS analysis of land use maps of Dublin in two points in time, 2006 and 2018, to examine the land use changes and evaluate the rate of urbanization. Since urban fabric increases impervious areas where rainfall accumulates and create strains in urban drainage systems, leading to flooding; the implications of urbanization and the impact of green roofs can have on stormwater management will be discussed.

1.4. THESIS STRUCTURE

Chapter 2 focuses on the literature review on green roof usage for stormwater management and the stormwater, flooding and climate change treats that Dublin city faces. Chapter 3 provides details on the site and the methodology for data monitoring and processing, meteorological and runoff calculations, green roof model parameterization and calibration and GIS analysis. Chapter 4 and 5 provides results and discussion on the outcomes. Finally, Chapter 6 offers the conclusions and recommendations on the study.

CHAPTER 2 LITERATURE REVIEW

2.1. GREEN ROOFS IN STORMWATER MANAGEMENT

Green roofs are vegetated surfaces composed by substrate, drainage, water proofing and structural base layers. They operate to intercept and store rainfall with their vegetation and substrate layer, to achieve infiltration and evapotranspiration which can reduce the amount of water (Kasmin, 2010). Many studies proved green roofs can reduce the volume of the runoff and the intensity of the peak flow while delaying it as well (Bengtsson, 2005, Stovin et al., 2012; Getter et al., 2007; Mentens et al., 2006). Also, several studies showed green roofs can contribute to stormwater management in a catchment scale together with other sustainable drainage and nature-based solutions like bioretention swales, infiltration beds etc. (Carter et al., 2007; Versini et al., 2015; Zahmathkesh et al., 2014; Damodaram et al., 2010; Qin et al., 2013; Schmitter et al., 2016). Shafique catalogued the performance of green roofs in run off retention and stated the studies vary between 50 to 80% with an average of 67% (Shafique, 2018). Overall, Mentens suggested a catchment scale runoff reduction of 2.7% if 10% of rooftops in Brussels were to be retrofitted with green roofs (Mentens et al., 2006). While Schmitter found 2.4% of run off reduction in Marina Reservoir in Singapore if all roofs were to be retrofitted. These performances depend on the implementation range of green roofs in a catchment area, green roof type and design configurations that include substrate type and depth, vegetation and drainage layer, climate conditions and the age of the roof (Stovin et al., 2012; Fioretti et al., 2010; Carpenter et al., 2016).

2.2. GREEN ROOF DESIGN

2.2.1. TYPES OF GREEN ROOFS

Green roofs are considered as a plant bed on a rooftop in a most basic sense, but their wide adoption and usages created more diverse designs. So, in order to standardize and create uniformity with the design parameters, a categorization based on the multilayer structure of green roofs is adopted in which the categories are identified as extensive and intensive green roofs and intermediary system called semi-intensive green roof (FLL, 2008). The structure differences in substrate depth, construction methods and vegetation types separate these types (Van Lennep et al., 2008). However, another approach for categorization was recently suggested by Kotze et al. wherein the functionality and purpose of the green roof are the decisive measures. In this work, it has been found that this mainly dual classification depends on too many variables that include substrate depth, organic material amount, vegetation type, roof weight, whether maintenance is needed or not, etc. Kotze reported there is much confusion in the literature concerning green roofs where a green roof which is identified as extensive can have the properties of intensive roofs (Kotze et al., 2020). The same issues were also encountered during this study. Furthermore, Kotze provides tentative alternative terminologies such as “stormwater meadow roof”, “biodiversity meadow roof”, “scenic moss roof”, “restorative forest roof”, “multifunctional meadow roof” etc. where function and vegetation type are emphasized. Kotze also highlights that this type of terminology may allow policy making and tax issues to be more manageable, as in a stormwater meadow roof can easily be identified as incentivized for stormwater impact fee (Kotze et al., 2020). The following section gives detail on traditional and currently accepted parameters for green roof types and reference Kotze’s terminological approach as well.

2.2.1.1. EXTENSIVE GREEN ROOFS

Extensive green roofs have typically a shallow substrate which is less than 100 mm, low organic content, furnished with low maintenance plants like succulents, sedum and grasses. They don’t typically require maintenance apart from during their installation and they don’t need to be irrigated (GRO, 2011). They can be built as inaccessible by the public. They are seen as the cheaper and easier to install and maintain than other types of green roofs (Van Lennep, 2008). Substrate depth is usually referred differently in different sources, for example, policy guidance report for green roofs in Dublin identifies extensive green roof substrate as 20 – 200 mm whereas in the UK, it is accepted as less than 100 mm (Van Lennep, 2008; GRO, 2011). This also depends on the vegetation as plants require different growing media depths. Native grasses can be classified as extensive due to their low maintenance but can be conflicting with their growing media depth (Van Lennep, 2008).

2.2.1.2. INTENSIVE GREEN ROOFS

Usually referred as a roof garden, intensive green roofs have thicker substrate layer which is typically higher than 200 mm, usually require irrigation and maintenance due to their higher canopy and complexity vegetation (GRO, 2011). Dublin’s policy guide identifies substrate depth for intensive roofs as 150-500 mm which partly coincides with extensive substrate depth, creating confusion Kotze mentioned (Van Lennep, 2008; Kotze et al., 2020). Due its larger thickness, intensive roofs are considered the heavier option, but the weight depends on the substrate material (Van Lennep, 2008; Kotze et al., 2020).

2.2.1.3. SEMI-INTENSIVE GREEN ROOFS

Semi-intensive roofs are the intermediate system between extensive and intensive roofs. Substrate depth is considered between 100-200 mm. Vegetation may include more complex plants than grasses and sedum, such as shrubs and small woody plants which irrigation and maintenance depend on (GRO, 2011). Dublin policy guide refers their substrate depth as the same with intensive roofs but exclude tree like plants from the vegetation selection (Van Lennep, 2008).

Perez summarizes the traditional categorization of green roof types in his study that is presented in Table 1.

TABLE 1 TRADITIONAL GREEN ROOF TYPOLOGIES (CREATED BY PEREZ ET AL., 2018

	EXTENSIVE	SEMI-INTENSIVE	INTENSIVE
WEIGHT AT MAXIMUM WATER CAPACITY	50 – 150 kg/m^2	120 – 350 kg/m^2	>350 kg/m^2
SUBSTRATE LAYER THICKNESS	60– 200 mm	100 – 250 mm	>250 mm
PLANT TYPOLOGIES	Succulent, herbaceous, and grasses	Herbaceous, grasses, and shrubs	Grasses, shrubs, and trees
SLOPE	<100%	<20%	<5%
IRRIGATION	Never or periodically	Periodically	Regularly
MAINTENANCE	Low	Moderate	High
COSTS	Low	Middle	High
USE	Only accessible for maintenance	Pedestrian areas but with a moderate use	Pedestrian/recreation areas

Perez's study also shows there are conflicting information about categorization parameters between academic studies and practitioners as Kotze suggested. It can also be said that the non-uniform identifications in the academic field leads to non-uniform approaches in the policy making around the world as the green roofs become more and more popular (Kotze et al., 2020).

2.2.2. PROPERTIES AND MAINTENANCE OF GREEN ROOFS

Adoption and acceptance of green roofs highly depend on the accessibility of structural properties. These parameters either facilitate or hinder incorporation of green roofs for projects involving environmental, social and/or economic benefits. They are also determinants of green roof performance which can vary from stormwater management, thermal and energetic performance enhancement, biodiversity improvement and social wellbeing (Bengtsson et al., 2005; Kasmin et al., 2010; Stovin et al., 2012; Morau et al., 2012; Getter et al., 2011; Gaffin et al., 2009; Nagase et al., 2014; MacIvor et al., 2014; Braaker et al., 2014; Mesimaki et al; 2018). The basic structure of a green roof is shown in Figure 2.

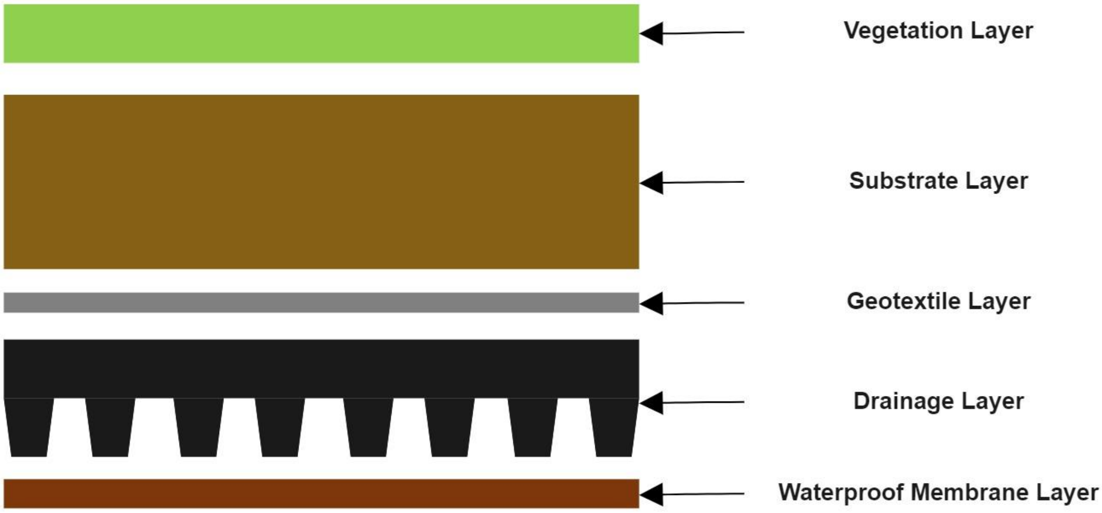


FIGURE 2 TYPICAL STRUCTURE OF A GREEN ROOF

2.2.2.1. IMPOSED LOAD OF GREEN ROOFS FOR BUILDINGS

Green roof load is especially important for retrofitting existing buildings. Load should be considered for wind, water saturated and/snow loaded weight and for shear force where green roofs are installed on a steep roof. Dry weight of the system should be safe from wind uplift while saturated weight should be safe for the building structure to carry it. For high slopes, anti-shear force measures like slip barriers are suggested (GRO, 2011).

2.2.2.2. WATERPROOFING GREEN ROOFS

Waterproofing can be done with waterproof membranes, liquid to solid waterproofing materials and metal structures to protect the actual roof and what’s below it (GRO, 2011). Waterproofing membranes can have a long lifecycle, at least 45 years which makes this step important for sustainability of the green roof (Kosareo et al., 2007).

2.2.2.3. DRAINAGE SYSTEM

Drainage layer is especially important in green roofs designed for stormwater management as they may contribute to water retention. The design should consider the water retention capacity along with providing enough permeability to accommodate high intensity storm events to prevent flooding on top of the roof (GRO, 2011). Carbone suggested using a higher water holding capacity drainage layer improves the retention performance even when the other performance indicators are unfavourable for retention like saturated substrate layer (Carbone et al., 2014). Drainage layers can vary from egg-box storage to mats and composite mixes (Carpenter et al., 2016; Carbone et al., 2014; Getter et al., 2011).

2.2.2.4. GROWING MEDIUM / SUBSTRATE

Growing medium evolved from garden soil to engineered media alternatives when leaching is observed when the organic matter content is high (Vijayaraghavan et al., 2014; Beecham et al., 2015). Substrate selection plays a vital role for water retention and run off quality. Substrate with higher water holding capacity performs better in retaining water and delaying peak run off (Vijayaraghavan et al., 2014). Substrate that can keep moisture for longer periods can improve plant survival, but it is also observed that short-rooted plants can’t use moisture from deeper substrate levels (Feng et al., 2018). However, keeping moisture for longer periods can also hinder water retention capacity. Bengtsson found out that run off from green roofs only generated when the green roof is saturated or reached its field capacity, so roofs ability to recharge to retain as much water as possible depend on its substrate drying between the rainfall events (Bengtsson et al., 2005). So, the design of growing medium depends on many parameters like the purpose of the green roof, the climate, the vegetation selection and the desired impact on its surroundings.

2.2.2.5. VEGETATION

Vegetation depends on the same parameters as the substrate. In terms of stormwater management, Vijayaraghavan found that vegetated roofs delay the runoff and reduce the runoff volume more than non-vegetated roofs due to plants’ water uptake and increased evapotranspiration (Vijayaraghavan et al., 2014). Beecham noted in climates with long antecedent dry weather period, where rainfall events have higher frequency, the retention performance depend on the existence of vegetation rather than the properties of the substrate while in the opposite conditions, the substrate selection is more important (Beecham, 2015). Plant survival is another key factor for roof sustainability, and it depends on the climate, meaning in hot and dry climates leaf succulence, plant’s ability to store water on its leaves, should be high while in wet climates this can cause problems (Rayner et al., 2016).

2.2.2.6. GREEN ROOF MAINTENANCE

Roof maintenance is defined based on roof type and includes initial establishment period and the rest of the lifecycle. The activities are irrigation, fertilizing, plant check and care and cleaning (GRO, 2011). The extent of maintenance requirements should be designed in advance to foresee a maintenance budget and scheme to have a sustainable green roof setting which won't deteriorate before its time. Fertilization can be a problem for runoff water quality as with substrate having high organic content the leaching is observed (Li et al., 2014; Kuoppamaki et al., 2016). As for irrigation, Nagase discussed careful design and selection of substrate and vegetation even intensive roofs can survive without irrigation and maintenance in humid tropical climates while in hot dry climates, Rayner showed plants can survive without irrigation if their leaf succulence is high (Nagase et al., 2014; Rayner et al., 2016). Feng studied the ideal amount of irrigation in intensive roofs in climates with rain scarcity and concluded that irrigation can be used to support evapotranspiration regime that balances plant life and the regeneration rate for water retention (Feng et al., 2018).

2.3. HYDROLOGICAL PERFORMANCE OF GREEN ROOFS

Hydrological performance refers to runoff reduction and peak discharge delay (Bengtsson et al., 2005). This is done by water uptake by the plant layer, infiltration, hence the delay in substrate layer and storage in the drainage layer in the roofs (Kasmin et al., 2010). Driscoll showed green roofs are capable of 73.2% runoff reduction and are the second-best stormwater technology type after bioretention basins (Driscoll et. al, 2015). Stovin, clearly showed green roofs can reduce runoff and delay discharge more than conventional roofs (Stovin, 2012). In Table 2, observed runoff retentions from the literature are listed, modified from Shafique's study.

TABLE 2 GREEN ROOF RUNOFF REDUCTION RATES FROM LITERATURE (MODIFIED FROM SHAFIQUE ET AL., 2018)

REFERENCES	OBSERVED RUNOFF RETENTION (%)	LOCATION
BENGTSSON ET AL., 2005	**62.0**	**LUND UNIVERSITY, SWEDEN**
KÖEHLER, 2005	**77.0**	**UNIV. OF NEUBRANDENBURG, GERMANY**
CENTGRAF, 2005	**77.0**	**TU OF BERLIN, GERMANY**
LUCKETT ET AL., 2006	**82.2**	**ILLINOIS, USA**
TILLINGER ET AL. 2006	**80.0**	**COLUMBIA UNIVERSITY, NY, USA**
PROWELL, 2006	**78.0**	**UNIV. OF GEORGIA, ATHENS, USA**
MENTENS ET AL., 2006	**76.0**	**KU LEUVEN, BELGIUM**
CARTER ET AL., 2006	**78.0**	**GEORGIA, USA**
GETTER ET AL., 2007	**80.8**	**MICHIGAN, USA**
SETERS ET AL., 2009	**63.0**	**TORONTO, CANADA**
FIORETTI ET AL., 2010	**68.0**	**NORTHWEST AND CENTRAL ITALY**
CARPENTER ET AL., 2011	**68.3**	**MICHIGAN, USA**
PALLA ET AL., 2011	**68.0**	**GENOA, ITALY**
STOVIN ET AL., 2012	**50.2**	**SHEFFIELD, UK**
STOVIN ET AL., 2013	**59.0**	**SHEFFIELD, UK**
MORGAN ET AL., 2013	**50.0**	**MICHIGAN, USA**
FASSMAN-BECK ET AL., 2013	**56.0**	**AUCKLAND, NEW ZEALAND**
VIJAYARAGHAVAN ET AL., 2014	**39.4**	**MADRAS, INDIA**
CARBONE ET AL., 2014	**30**	**CALABRIA, ITALY**
BEECHAM ET AL., 2015	**51-96**	**ADELAIDE, AUSTRALIA**
SHAFIQUE ET AL., 2016	**68.0**	**SEOUL, KOREA**
CARPENTER ET AL., 2016	**88-95**	**NEW YORK, USA**
SHAFIQUE ET AL., 2018	**10-60**	**SEOUL, KOREA**

It can be observed that the performance varies greatly between these studies. There are many interconnected reasons effecting the performance which were briefly mentioned in Chapter 2.2 which mainly depend on green roof type and design parameters, vegetation selection and local climate conditions.

2.3.1. HYDRAULIC PERFORMANCE BASED ON GREEN ROOF TYPE AND DESIGN

The literature on extensive green roof performance is more diverse than studies on intensive roofs as they are easier to implement and replicate. Beecham showed intensive roofs have higher retention performance than extensive roofs as they have more robust vegetation that can take up more water and enhance evapotranspiration more, thicker substrate layer in which infiltration takes more time and higher water storage is possible (Beecham et al., 2014).

Green roofs having larger drainage storage can retain more water and delay discharge but being only a mechanical delaying mechanism, the performance should be enhanced by careful design of substrate and vegetation. In Carbone's study, the performance is relatively low (30%) compared to other studies in Mediterranean or similar climates which can be related with selected substrate having less water holding capacity (silt and sand) as Vijayaraghavan proved substrate water holding capacity play a great role in retention (Carbone et al., 2014; Vijayaraghavan; 2014). Corey also noted drainage layer capacity is a factor for runoff retention and can mitigate seasonal performance difference by holding high intensity precipitation during wet season when the substrate is saturated (Carpenter et al., 2016).

Performance is directly linked with moisture content of substrate level, when it is saturated the runoff from the roof is instant (Bengtsson, 2005; Shafique, 2018). Soil moisture is low when there is a long antecedent dry period and high when there is high intensity and/or high frequency rain events. So, it is a decisive factor for green roofs to regain retention capacity hence reduce runoff and delay discharge (Kasmin et al., 2010).

2.3.2. HYDRAULIC PERFORMANCE BASED ON VEGETATION

When antecedent dry period is longer, vegetation gains more importance than the substrate as plants increases retention capacity by water uptake and evapotranspiration after being subjected to a long dry period (Beecham et al., 2015). Vegetated roofs are better in delaying and reducing runoff than plain substrate ones (Vijayaraghavan et al., 2014). Plants can be chosen for their root depth to enable access to deeper moisture levels and leaf succulence to avoid rotting in wet climates and wilting in dry climates (Rayner et al., 2016; Feng et al., 2018).

Furthermore, evapotranspiration rate is highly dependent on the type of vegetation used in green roofs. As evapotranspiration plays an important role in runoff reduction, vegetation selection is a crucial element of green roof design for stormwater management. Crop coefficients are used to determine water requirements of vegetation usually in agriculture and they are based on evapotranspiration rates of plants. Plants having high crop coefficients have lower water demand due to high evapotranspiration potential. For example cotton is known as a high water demand plant while mint is known for its drought tolerance, their crop coefficients are 0.5 and 1.1 respectively making mint a better option for runoff reduction with its increased potential for evapotranspiration (Glenn et al., 2011).

2.3.3. HYDRAULIC PERFORMANCE BASED ON CLIMATE CONDITIONS

Rainfall frequency and intensity highly affects the hydrological performance. When rainfall is frequent, the moisture level in the substrate remains high which reduces the retention capacity (Carpenter et al., 2016). Water content in the substrate slowly reduces after the end of the rain event but the drop is a slow process so long antecedent dry period is necessary to regenerate the retention potential of the roof (Carbone et al., 2014). However, in arid climates the balance between the dryness to the wilting point and the minimum moisture level can be difficult to achieve (Bengtsson et al., 2005; Chen et al., 2011). In wet climates, substrate doesn’t dry out between the rain events, reducing the overall retention capacity (Bengtsson et al., 2005; Vijayaraghavan et al., 2014). However even when the substrate is partially saturated Corey noted, with low intensity rain the water retention can be between 98% and 100% while it reduces to 88% when the substrate is fully saturated following a short dry antecedent period and high intensity rainfall (Carpenter et al., 2016).

Evapotranspiration is another important factor for the performance. Evapotranspiration changes seasonally and in summer when evapotranspiration is high, the runoff from the roof is low as retained water is reduced with it (Bengtsson et al., 2005). Evapotranspiration rates are studied to be able to standardize them for local climate and substrate type by Kasmin and an adaptation of a rate calculation formula is suggested to enable a more accurate roof design for specific climates (Kasmin et al., 2010).

Schmitter noted also rainfall variability concerning intensity and antecedent dry period and green roof parameters have significant impact on catchment scale run off volume reduction which is important for tackling flooding in urban setting (Schmitter et al., 2016).

2.4. POLICIES FOR GREEN ROOFS

It is established that green roofs contribute to sustainable stormwater management by runoff reduction and discharge delay. Their acceptance and adoption however are related with policies and incentivization to enable their replicability. High initial and sometimes operational costs, lack of awareness and incentives and socio-institutional barriers involving the fact that traditional solutions are faster, well known and recognized and can remove the problem from local setting by carrying it elsewhere (discharge to waterbodies or treatment plants cause limitations for adoption of green roofs (Dhakal et al., 2017; Chen et al., 2019). It is argued that policy interventions and incentivization are necessary to widen the application of green roofs (Brudermann et al., 2017).

Irga noted Europe and North America have the most advanced green roof policies and incentives in the world. While Europe is even more progressive in their policies to widen the application (Irga et al., 2017). According to Gary's study, in 2015, Austria, Germany and Switzerland have the largest green roof footprint while the leading cities are Basel, Stuttgart and Linz (Gary et al., 2019). Chen stated the USA, Canada, Australia, Singapore and Japan are top countries encouraging green roofs (Chen et al., 2019).

The list of international policies and incentives governing green roof implementations are created by Dong in 2020 and given in Table 3. The existing major policies show financial support and incentivization have utmost importance and dominates the top green roof implementing countries. Liberalesso argued these mechanisms lack variability, mainly focusing on financial incentives and legal obligations (Liberalesso et al., 2020). Furthermore, it is concluded that in North America the incentives types are more balanced, being 23% subsidies, 18% obligation by law, 15% stormwater discount, 15% sustainability certification while in Europe, 85% of the incentives are financial incentives (Liberalesso et al., 2020). So, it is safe to assume the rapid development in North America depends on a balanced approach to green roof incentivization.

TABLE 3 INTERNATIONAL POLICIES CONCERNING GREEN ROOFS (MODIFIED FROM DONG ET AL., 2020; IRGA ET AL., 2017; GARY ET AL., 2019)

REGION	CITY	POLICY	DETAILS	OUTCOME
EUROPE	Basel, Switzerland	Building and Construction Law (BCL), 1996–1997, 2002, and 2005–2006	Green roofs to new and renovated buildings, \$20.5/m^2 subsidized for GRs	100 ha by 2015
	Stuttgart, Germany	City of Stuttgart regulations, 1986; Climate Atlas, 2008; German Building Code (GBC), FLL Green Roof Guidelines, 2008	Subsidies, planning and technical guideline, mandating flat roofs to become GRs	30 ha by 2015
	Linz, Austria	City building codes, 1985; Green space program	Obligation for new buildings to have GRs, 30% until 2005, 5% until 2016 reimbursement of the costs	50 ha by 2015
	London, UK	London Plan, 2008; Living Roofs and Walls Guidance Note of 2008, Green Roofs and Development Site Environs Policy and Urban Greening Policy within London's Response to Climate Change, 2015, Biodiversity Action Plan, 2010–2015, Green Roof Map, 2013	Technical and planning guides and strong encouragement	150 ha by 2017
	Copenhagen, Denmark	Copenhagen Climate Plan, 2025, Sustainability in Constructions and Civil Works (SCCW), Green Roofs Copenhagen Guidance Note, 2012	Mandating municipal buildings and roofs having less than 30^o slope to have GRs	40,000 m^2 by 2015
	France, State level	Biodiversity, Nature and Landscapes Law, 2016	New and commercial buildings to have GRs	1 million m^2 in 2017
AMERICA	Washington, USA	Clean Water Act, 1987, RiverSmart Programs, 2007, Stormwater Retention Credit Training Program, 2013, Washington DC Municipal Management Regulations (DCMR), 2013, Green Roof Rebate Program, 2016, Green Area Ratio, 2017	Stormwater management and green area ratio measures, \$5/ft^2 tax free funding for GRs	2.6 million m^2 by 2015

	Portland, USA	Ecoroof Requirement Private Property Retrofit Program, 2018, Green Building Policy, 2001, Clean River Rewards, 2005, Stormwater Management Manual, 1999	Large new buildings (20,000 ft^2) to have green roofs, stormwater impact fee discount	15.8 ha by 2015
	Chicago, USA	Sustainable Development Policy, 2017, Green Roof Incentives, 2015, Green Permit Program, 2014, Adding Green to Urban Design Plan, 2008, Sustainable Development Policy, 2007, Green Roof Improvement Fund, 2006, Green Roof Grant Program, 2005	Reward points for GRs where new developments should reach 100 points, reduced permit fees, priority development review, different financial incentives	50.8 ha by 2015
	Toronto, Canada	Green Roof Bylaw, 2009, Eco-Roof Incentive Program, 2009, Guidelines for Biodiverse Green Roofs, 2013	New commercial and institutional buildings with 2000 m^2 area to have GRs, 250 m^2 public buildings to be greened, new developments to have 20% GR area	500,000 m^2 by between 2009-2018
AUSTRALIA	Sydney, Australia	Green Roofs and Walls Policy, 2014, Environmental Performance Grants supported by Sustainable Sydney, 2030	Guides and manuals, grants and subsidies	23% GR and green wall coverage since 2014
	Melbourne, Australia	Growing Green Guide, 2014, Green Our City Strategic Action Plan, 2017-2021	Guides and manuals, public-private partnership co-financing facilitation	54,000 m^2 by 2015
ASIA	Tokyo, Japan	Tokyo Green Plan, 2012, Green Building Program, 2002, Tokyo Metropolitan Condominium Environmental Performance Labelling System, 10 Year Project for Green Tokyo, 2006, National Building Law, 2005	Mandating large public and private buildings to be greened, 20% of GRs to new apartments and office buildings	134.5 ha by 2015
	Singapore, Republic of Singapore	Skyrise Greenery Incentive Scheme, 2009 (SGIS), SGIS 2.0, 2015, Landscaping for Urban Spaces and High-Rises, 2009 (LUSH), LUSH 2.0, 2014	50% remuneration for costs, incentives and development exemptions	72 ha GRs and green walls by 2016

China, State level	Strengthening Urban Greening Construction, 2001, Urban Garden Greening Evaluation Standards, 2010, National Garden City Series Standards, 2016	Technical guides and evaluation standards, development encouragement	2.6 million m^2 in Shenzhen, 2.1 million m^2 in Beijing, 2.1 million m^2 in Shanghai

2.5. CLIMATE CHANGE AND URBANIZATION IMPLICATIONS FOR DUBLIN

Dublin is in a significant development trend since 1990s (Ellis et al., 2001). Rapid urbanization followed big economic development, but traditional urban development approach made the city more impervious in time. The traditional system favours that the collected stormwater bypasses the natural environment to the treatment plant and discharge to a usually far away waterbody. Dublin was also subjected to this like many cities in Europe until the Greater Dublin Strategic Drainage Study in 2005, which mandates the use of sustainable drainage systems (Fleming et al., 2005). A Flood Studies Update was issued in 2005 to tackle urban flooding with an emphasis of alternative stormwater management systems (O'Sullivan et al., 2012). Since the inclusion of SUDs in the policy, the discharge water quality along with the discharge frequency and intensity gain more importance to mitigate flooding issues (O'Sullivan et al., 2012). Today, Dublin Climate Change Action Plan include flood resilience target that covers the use of nature-based solutions and SUDs, including green roofs, to reduce the risk of flooding (Dublin City Council, 2019).

Studies identified barriers to implement SUDs, which include green roofs, in Ireland as:

- Ownership related with the responsibility of maintenance costs,
- Capital costs,
- Available land and land taking,
- Uncertainty of the performance of SUDs in reducing and delaying the runoff and improving its quality,
- Doubts related with performance during extreme storm events,
- Resistance from the practitioners due to above mentioned perceptions,
- Insufficient promotion of SUDs in planning policies (White et al., 2009),
- Lack of legislative direction for collaboration between local authorities concerning cross boundary catchments (O'Sullivan et al., 2012; Rooney et al., 2018).

Dublin experienced three major floods in the last decade which were originated from river, coastal and rainfall related flooding (Leahy, 2011). Having a coastal shore, crossed by three rivers, namely Dodder, Liffey and Tolka, and receiving heavy precipitation and storms, Dublin is identified as a flood prone city (Lhomme, 2019). Leahy notes the conventional stormwater networks often are overwhelmed and traffic related structures can be saturated rapidly and sometimes may need to discharge water with external pumps (Leahy, 2009).

These conditions will be worsened with the impacts of climate change in Dublin. Major identified risks due to climate change in Dublin are sea level rise, flooding and extreme weather events like storms, cold spells and heatwaves, (Dublin City Council, 2019). EPA's precipitation model for Ireland based on climate change scenarios indicate that the number of wet days will decrease while the average number of heavy precipitation (>10mm) and very heavy precipitation (>20mm) days will increase in Dublin for all scenarios (EPA, 2018).

Hawchar found out that rising sea levels and increased storm events will impact the critical infrastructure like roads, railways, airports and ports. He noted especially fluvial flooding may critically damage transport and wastewater treatment infrastructure while coastal flooding and erosion due to rising sea level will pose a threat as well. Hawchar's risk index puts Dublin within the high-risk group (Hawchar et al., 2020).

In conclusion, under climate change and urbanization implications, considering the benefits of sustainable stormwater management systems including green roofs and barriers for their adoption and acceptance in Ireland and elsewhere in the world; case studies related with their performance, local and regional impacts, their behaviours in future climatic conditions should be further researched and presented to the literature.

CHAPTER 3 METHODOLOGY

The run off performance of green roofs can be measured based on their ability to decrease total run off volume, peak flow and/or to increase peak flow time. These analysis can be based on either a monitoring or a modelling based approach. Monitoring based approach relies on real data collected taken from an actual green roof and a comparison between run off data with and without the green roof. Modelling approach relies on simulated data that can be based on both real and hypothetical run off data using real meteorological data. This study is based on a simulation model that uses real data from an existing green roof pilot to simulate run off under current meteorological conditions and under implications of climate change.

3.1. GREEN ROOF SETUP

Green roof units are deployed in the CHQ building in the city centre of Dublin (53°20'55.6"N 6°14'50.8"W) in February 2021. A total of 70 modular trays were used, each with an area of 1 m^2, making the total green roof area 70 m^2. The modular trays are shown in Figure 3. The substrate is commercially available loamy soil and its thickness is 80 mm and the vegetation is selected as commercially available sedum mat. 4 modular trays are chosen for data collection.

FIGURE 3 MODULAR GREEN ROOF TRAY

In order to observe run off reduction, the mass of the selected trays are measured in 10 minute intervals with a weight sensor having 0.1 grams accuracy. The run off reduction is estimated through the changes in the mass of the beds. Furthermore, weather variables necessary for the modelling are obtained by a weather station (Figure 4) situated on site registering solar radiation, wind speed, relative humidity in an hourly fashion. Rainfall and temperature are observed with a rain gauge, shown in Figure 4, and a temperature sensor respectively in 10 minute intervals. The data collection was planned for the period beginning from 21st February to 21st May, 2021 however, because of COVID-19 restrictions, the data collection from the site was disrupted. In consequence, data collection was possible only between 21st February and 28th February 2021.

FIGURE 4 WEATHER STATION AND RAIN GAUGE

3.2. MODELLING METHODS

There are few studies in which hydrological models that simulate green roof run off reduction. The most commonly used one being Storm Water Management Model (SWMM) allows modelling the green roof water cycle followed with Conceptual Hydrological Flux Model, HYDRUS-1D, MIKE-SHE, Modelling of Urban Sewers, Soil Conservation Service Curve Number, Sobek, System for Urban Stormwater Treatment and Analysis Integration, Soil Water Atmosphere and Plant and SWMS-2D models. Table 4 summarizes the different models used by researchers to simulate green roof runoff.

TABLE 4 LITERATURE SUMMARY ON GREEN ROOF RUNOFF MODELLING

MODELLING TOOL	RESEARCHERS
SWMM	Burszta-Adamiak and Mrowiec, 2013; Oviedo and Torres, 2014; Shin and Kim, 2015; Masseroni and Cislaghi, 2016; Giacomoni and Joseph, 2017
CONCEPTUAL HYDROLOGICAL FLUX MODEL	Stovin et al., 2013
HYDRUS-1D	Hakimdavar et al., 2014; Palermo et al., 2019
MIKE-SHE	Zölch et al., 2017
MODELLING OF URBAN SEWERS	Liu and Li, 2016
SOIL CONSERVATION SERVICE CURVE NUMBER	Roehr and Kong, 2010; Liu et al., 2017
SOBEK	Schmitter et al., 2016

MODELLING TOOL	RESEARCHERS
SYSTEM FOR URBAN STORMWATER TREATMENT AND ANALYSIS INTEGRATION	Gao et al., 2015
SOIL WATER ATMOSPHERE AND PLANT	Metselaar, 2012
SWMS-2D	Palla et al., 2011

It has been observed that most of these models apply a minute/hourly scale followed by daily, monthly and annually scale analysis. The modelling approach allows the simulations for different portions of buildings in area that are retrofitted to estimate the runoff reduction under different retrofitting scenarios. The models however, require to be validated with real observed data to reflect on the runoff reduction accurately. Only a few studies include model validation using observed green roof runoff data (Palla et al., 2011; Burszta-Adamiak et al., 2013).

3.3. SIMULATION SETUP

In this study, SWAT model is used due to its ability to simulate hydrological processes for long periods of time (Abbaspour et al., 2007; Jha et al., 2006; Santhi et al., 2001) and effective in simulating changes in the water quantity as well as quality. SWAT uses a modified NRS curve number method to simulate surface runoff and is developed to be used in agriculture sector to estimate the water quantity and quality that effects crops. Now, many studies show SWAT has the flexibility to simulate runoff in different environments with various land uses, including urban environment (Hajihosseini et al., 2020; Yang et al., 2011; Seo et al., 2017). SWAT is used to examine the impact of low impact development practices on runoff in several studies. It is possible to simulate physical and biological conditions formed by green roofs, urban swales, retention/filtration basins, detention ponds etc. to evaluate how they behave under different weather conditions and designs. These studies suggest SWAT is flexible enough to modify inputs for green infrastructure simulations and reliable enough to be used as a tool for design and planning (Seo et al., 2017; Jeong et al., 2011; Jeong et al., 2013). All calculations are carried out using MATLAB software.

3.4. DATA COLLECTION

Historical meteorological inputs (Temperature, precipitation, wind speed, relative humidity, all at hourly scale) were obtained from MET Eireann (Eireann, 2020), for the weather station located at Dublin Airport. The station is located at 73 m altitude from sea level. The data registered between 1st January 1990 to 1st March 2020. These historical data is used for the model calibration and validation. Daily variables were calculated from the hourly data for total precipitation, maximum and minimum temperature and relative humidity, mean wind speed and daily relative sunshine duration. It should be noted that the Dublin Airport weather station is actually 11 km away from the pilot green roof site as presented in Figure 5, which may affect some of the meteorological variables, especially the wind speed.

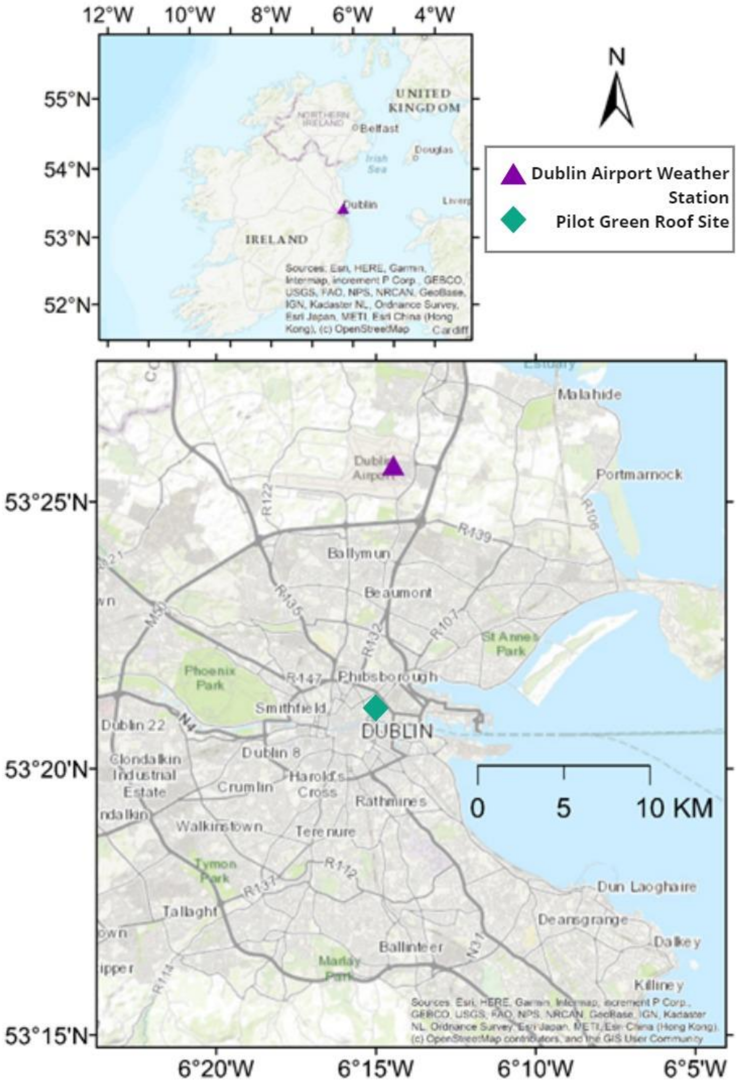


FIGURE 5 LOCATION OF THE DUBLIN AIRPORT WEATHER STATION AND THE GREEN ROOF SITE

Climate change projection data is obtained from the EURO CORDEX which is the European branch of the international CORDEX initiative that works on producing regional climate change projections. Regional Climate Model (RCM) simulations made by the Rossby Centre of Swedish Meteorological and Hydrological Institute (SMHI) are selected to be used in the model. The simulation data were published via Earth System Grid Foundation (ESGF) which is an international cooperative targeting deployment and maintenance for the management, dissemination and analysis of different climate model outputs to improve scientific background on earth systems (Swedish ESGF, 2021). The selected ensemble data provides meteorological variables between 1st January 1981 and 31st December 2100 and was accessed from Swedish ESGF node (Swedish ESGF, 2021).

Two RCP scenarios are chosen for the analysis:

- RCP 4.5: Strategies for reducing greenhouse gas emissions cause radiative forcing to stabilise at 4.5 W/m² before the year 2100 (IPCC, AR5).
- RCP 8.5: Increased greenhouse gas emissions mean that radiative forcing will reach 8.5 W/m² by the year 2100 (Kovats et al., 2014).

3.5. MODEL SETUP TO EVALUATE GREEN ROOF PERFORMANCE

The green roof performance evaluation using observed meteorological conditions with SWAT tool is based on an unpublished study by Bidroha Basu which is elaborated further in the limitations section of this work.

The runoff reduction performance of green roofs is assessed through estimating the overall runoff and the volume of water reduced by the presence of the green roof. Below equation shows the water balance is used to calculate runoff generated from the green roof.

$$\boldsymbol{RO = P - ET - \Delta SMC}$$

RO represents the overall runoff from the green roof which are overland flow and infiltration; P denotes the observed precipitation which is the actual runoff in the absence of a green roof; ET is the evapotranspiration and ΔSMC represents the change in the soil moisture content. The time step of the variables in the equation are considered in daily scale. The input data requirement, the intermediate data calculations and their relationship with the intended output of the model is presented in Figure 6.

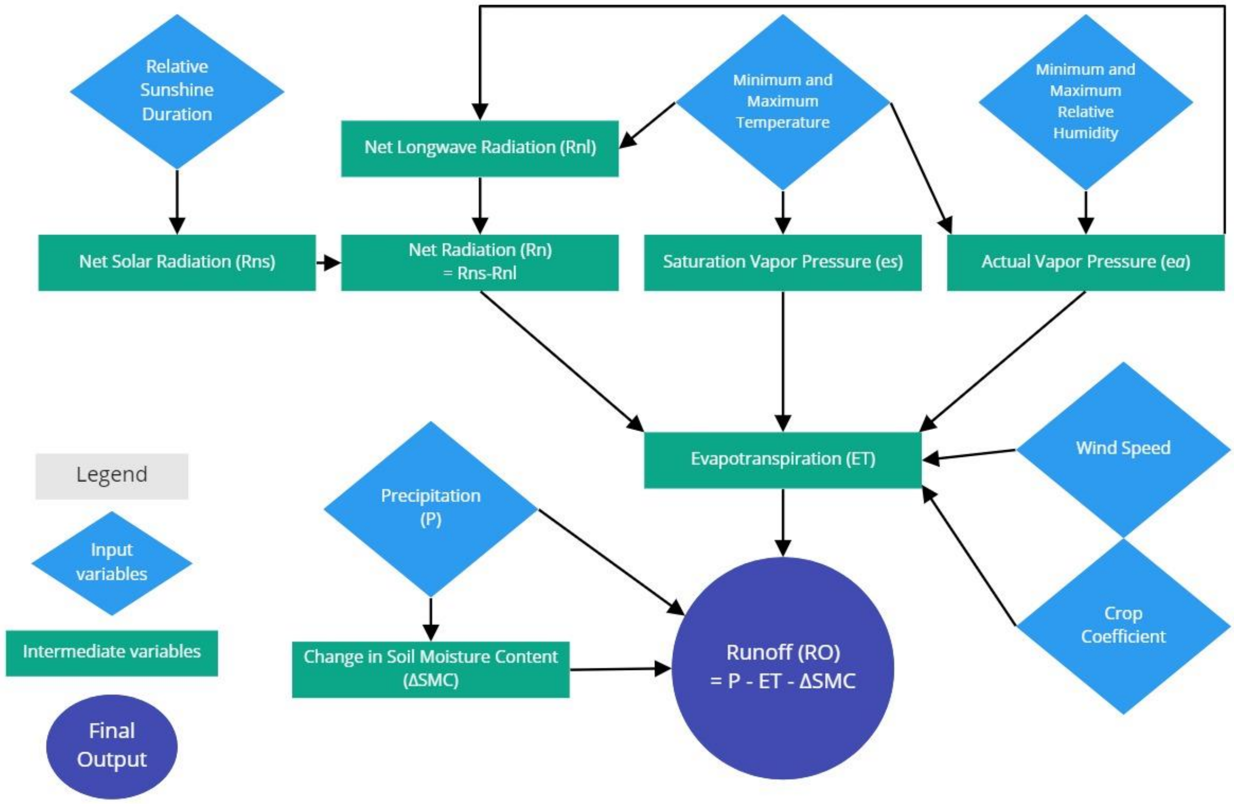


FIGURE 6 FLOWCHART OF THE SIMULATION MODEL TO ESTIMATE THE DAILY RUNOFF FROM THE GREEN ROOF

In the model, precipitation values measured by the rain gauge in the pilot site are used for the calculation purposes while the ET is calculated with Penman-Monteith method and modelled using the combined aerodynamic and energy balance method (Monteith, 1965). Daily maximum, minimum, and average temperature, daily maximum and minimum relative humidity, daily average wind speed and daily sunshine duration data are registered by the weather station and used for the calculation of ET. The crop coefficients are taken from the literature. For the changes in SMC, it is assumed that soil completely dries between rain events which affects the runoff reduction potential of the green roof.

The existing pilot green roof vegetation consists of sedum vegetation layer as mentioned but in order to compare the effect of different type of vegetation, 4 different vegetation types are modelled while sedum is used for model validation purposes. Sedum is selected as it is commonly used in green roof application, strawberries and mint were considered as added value plants, one being a fruit, the other being an aromatic or medicinal plant (Liu et al., 2019; Baudoin et al., 2017); while cotton is selected as a representative for cash crop category. The selected crops were sedum, strawberries, cotton and mint with crop coefficients of 1.0, 0.75, 0.5, and 1.1, respectively (Allen et al., 1998). Two different soil depths, 80 mm and 150 mm were also modelled to simulate the differences in water storage capacity. 80 mm is considered representative for extensive green roofs while 150 mm represents semi-intensive or intensive type. Furthermore, the soil type is chosen as clay having the water depth capacity of 175 mm/m of soil according to FAO guidelines (Brouwer et al., 1985). So overall, with the inclusion of different vegetation and soil types, eight cases were modelled using the observed current day data as shown in Figure 7.

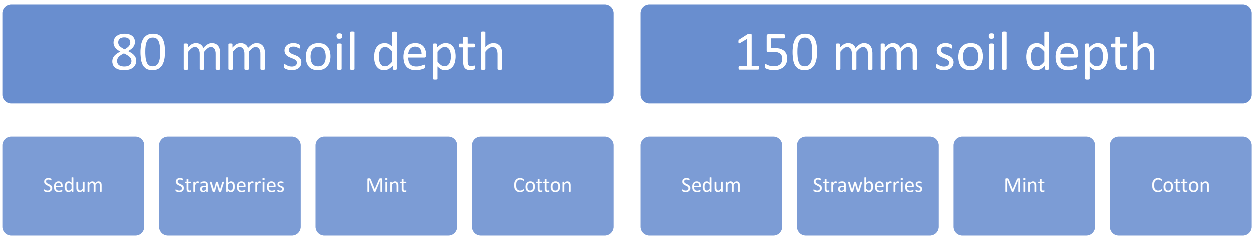


FIGURE 7 EIGHT MODELLED CASES FOR THE CURRENT DAY RUNOFF PERFORMANCE MODELLING

In order to assess performance, the runoff without the green roof is considered to be same with the actual precipitation so, the difference between the runoff with the green roof and without the green roof is estimated at a daily scale. Since the performance of the green roof highly depends on the intensity of the rainfall events (Carpenter et al., 2016), the results were categorized based on different rainfall intensities; being greater than 50 mm, 30 mm, 20 mm and 10 mm; allowing the analysis of the performance for different rainfall events.

3.6. MODEL VALIDATION

To validate the model, actual runoff from the green roof is measured through the changes in mass of the modular beds and compared with the modelled runoff which used the calculations and Figure 6 to simulate the runoff. As mentioned, since data collection from the site was disrupted because of COVID-19 restrictions, only data between 21st February and 28th February, 2021 could be used to validate the model. The differences between the model output runoff and the actual runoff is calculated using three different statistical approaches to check whether the differences could be reasonable in order to validate the model. The statistical approaches are given below

- Nash-Sutcliffe Efficiency (NSE):

$$NSE = 1 - \frac{\sum_{t=1}^{T}[\hat{y}(t) - y(t)]^2}{\sum_{t=1}^{T}[y(t) - \bar{y}]^2}$$

- Pearson correlation coefficient (CORR):

$$CORR = \frac{T\sum_{t=1}^{T}\hat{y}(t) \times y(t) - [\sum_{t=1}^{T}\hat{y}(t)] \times [\sum_{t=1}^{T}y(t)]}{\sqrt{\left[T\sum_{t=1}^{T}\left(\hat{y}(t)\right)^2 - (\sum_{t=1}^{T}\hat{y}(t))^2\right] \times \left[T\sum_{t=1}^{T}\left(y(t)\right)^2 - (\sum_{t=1}^{T}y(t))^2\right]}}$$

- Kling-Gupta Efficiency (KGE):

$$KGE = 1 - \sqrt{(CORR - 1)^2 + (a - 1)^2 + (b - 1)^2}$$

where $CORR$ is the Pearson correlation coefficient,

$$a = \sqrt{\frac{T\sum_{t=1}^{T}\left(\hat{y}(t)\right)^2 - \left(\sum_{t=1}^{T}\hat{y}(t)\right)^2}{T\sum_{t=1}^{T}\left(y(t)\right)^2 - \left(\sum_{t=1}^{T}y(t)\right)^2}}, \text{ and } b = \sqrt{\frac{\sum_{t=1}^{T}\hat{y}(t)}{\sum_{t=1}^{T}y(t)}}$$

and where;

$y(t)$ = the observed runoff at time t,

$\hat{y}(t)$ = the model predicted runoff at time t,

T = the number of daily data points,

$\bar{y} = \sum_{t=1}^{T} y(t)/T$ = the mean observed runoff.

The value of NSE and KGE should be within the range of $(-\infty, 1]$, while for CORR the range is $[-1,1]$. For the model to be consistent with the observed data, these values of all three error measures NSE, KGE and CORR are expected to be close to unity which means the model is actually able to represent the reality (Nash & Sutcliffe, 1970; Kling et al., 2012).

3.7. SIMULATION FOR CLIMATE CHANGE PROJECTION DATA

Climate change models are used to simulate the effects different greenhouse gas emission and radiation scenarios. They can be used to estimate future changes in the climate. The models are developed with supercomputers, relying on complex and long calculations and simulate the exchange between energy and mass in the atmosphere. While global climate models (GCMs) have 100 to 200 km grid resolution, regional climate models (RCMs) have finer resolution, i.e. 10-50 km, allowing capturing more nuance in a specific region (Hannah, 2015). However, since climate is not isolated from region to region and has interdependency, RCMs are used together with GCMs or other RCMs to simulate more accurate results.

The scenarios that the models rely on, first, depend on assumptions on future emissions, development of the world economy, population growth, globalisation, increasing use of green technology etc. which are called (Special Report on Emission Scenarios) SRES scenarios (Nakićenović, 2000). Second, they are based on radiation changes according to GHG effect and are called RCP scenarios - Representative Concentration Pathways (Moss et al., 2010).

Currently produced climate scenarios use radiation scenarios, GCM, RCM and the modelling time period.

3.8. BIAS CORRECTION

For this study, the climate scenario developed by SMHI is used and scenarios for RCP4.5 and RCP8.5 is selected. It should be noted that GCMs and RCMs usually exhibit large biases compared to the observed datasets due to model parametrization, inadequate data, low quality data or low spatial resolution (Mearns et al. 2012). So, several bias correction methods are developed to enhance the accuracy of the models. As models also simulate historical climate, it can be possible to correct these biases using different methods, such as bias correction which considers mean, variance, and peak values of a distribution, quantile mapping (QM) which are used for especially precipitation as it applies bias correction to all intended quantiles, change factor; if the observation data and the historic simulations have enough correlation between them (Hawkins et al., 2013; Tabor et al., 2010; Gudmundsson, 2012). Teng reported QM provide a better performance for runoff models than simple statistic bias correction where data is adjusted according to mean and variance while Themessl recorded QM has the best performance in correcting precipitation biases where simulation data is assumed to retain the same distribution of the observe data and simulated data which has a set probability is interchanged with the observed data with the same probability (Teng et al., 2015; Themessl et al., 2011). Quantile delta mapping (QDM) is developed by Cannon who described it as more reliable in providing results for preparing simulation data for climate change scenarios as it considers relative changes in all quantiles as the same (Cannon et al., 2015). In this study QM method developed by Li et al. is selected called equidistant CDF matching method (EDCDFm). This method uses cumulative distribution function (CDF) and adjusts it according to the difference between the CDF of the model and the CDF of the observations, so it allows to correct distribution changes between the model and observations (Li et al., 2010). This method is described in as:

$$(\widetilde{x}_{m-p.adjusted} = x_{m-p} + F_{o-c}^{-1}\left(F_{m-p}\left(x_{m-p}\right)\right) - F_{m-c}^{-1}(F_{m-p}\left(X_{m-p}\right))$$

where $\widetilde{x}_{m-p.adjusted}$ is bias corrected runoff value, x_{m-p} is model projected runoff and F is for CDF of either model (m) or the observations (o) for projected (p) or observed past values (c). The differences between the model and observations are subtracted from the actual observed data to find the bias corrected values for every data point. As naturally precipitation is not continuous but intermittent, the distribution of the events are also need to be corrected since climate change models usually estimates rain events to happen almost every day. So a gamma distribution model is used to simulate more accurate rain event distribution. MATLAB’s gamma distribution function which uses Method of Moments method is used for this calculation. The formula is given as

$$f(x;k;\theta) = \frac{x^{k-1}e^{-\frac{x}{\theta}}}{\theta^k \Gamma(k)} \; for\; x > 0\; and\; k, \theta > 0$$

$$\boldsymbol{k} = \frac{\boldsymbol{E}[\boldsymbol{X}^2]}{\boldsymbol{V}[\boldsymbol{X}]} \quad \boldsymbol{\theta} = \frac{\boldsymbol{V}[\boldsymbol{X}]}{\boldsymbol{E}[\boldsymbol{X}]}$$

where Γ(k) is the gamma function evaluated at k, k and θ are shape and scale functions, E is the mean, V is the variance and X is the value to be evaluated.

The visualization of the method is provided by Li et al. and shown in Figure 8. In order to carry out bias correction, CDF of the of the model projection values is found and locate the observed values in the same CDF quantile. (Li et al., 2010).

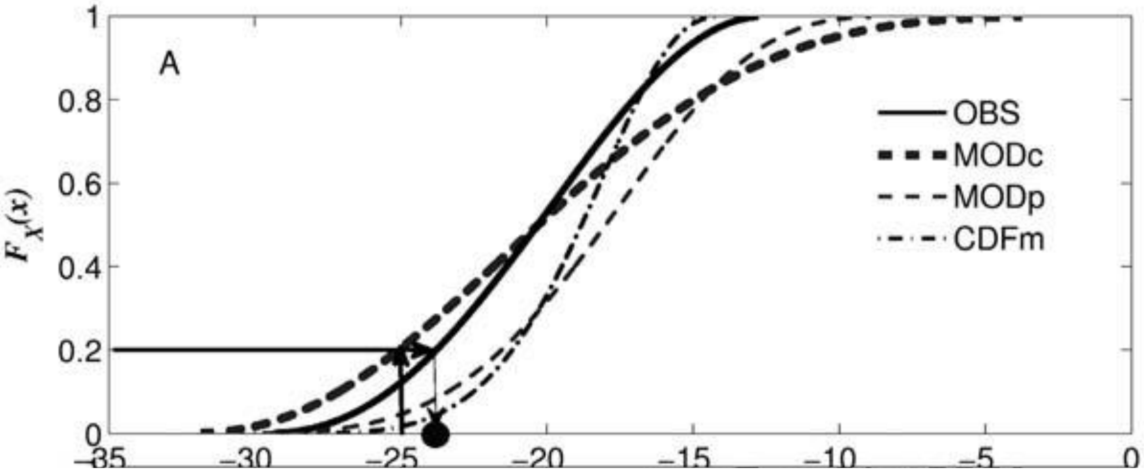


FIGURE 8 VISUALISATION OF THE BIAS CORRECTION METHOD (LI ET AL., 2010)

It should be also noted that bias correction can also be misleading as some studies show bias corrected long term climate data perform worse than the original GCM or RCM data (Maurer et al., 2014; Maraun, 2013). If the resolution of the observed data is much higher, it is noted that the QM method develops problems of inflation of data, misleading spatial and temporal structure, overly corrected drizzle effect data and overestimated extreme events (Maraun, 2013). Since the model in this study is a highly nonlinear model, bias correction of the input variables will lead to even higher bias in the output, so bias correction in this study is applied to the output values of the model, being the runoff.

Considering the reliability of the climate change model data, it is known that climate change models tend to overestimate precipitation in Europe, in terms of the number of wet days and the amount of rainfall. The reliability of the SMHI model is assessed as shown in Figure 9. As the model uses nine members of an ensemble, if all of them presents similar type of change (increase or decrease), it can be assumed that the model has a degree of robustness. The reliability of the temperature projection over Dublin seems robust as 8 of the members show similar increase in RCP4.5 and 9 for RCP8.5 while for precipitation, the reliability is significantly lower with 6 to 7 members showing similar increase in RCP4.5 and RCP8.5 respectively.

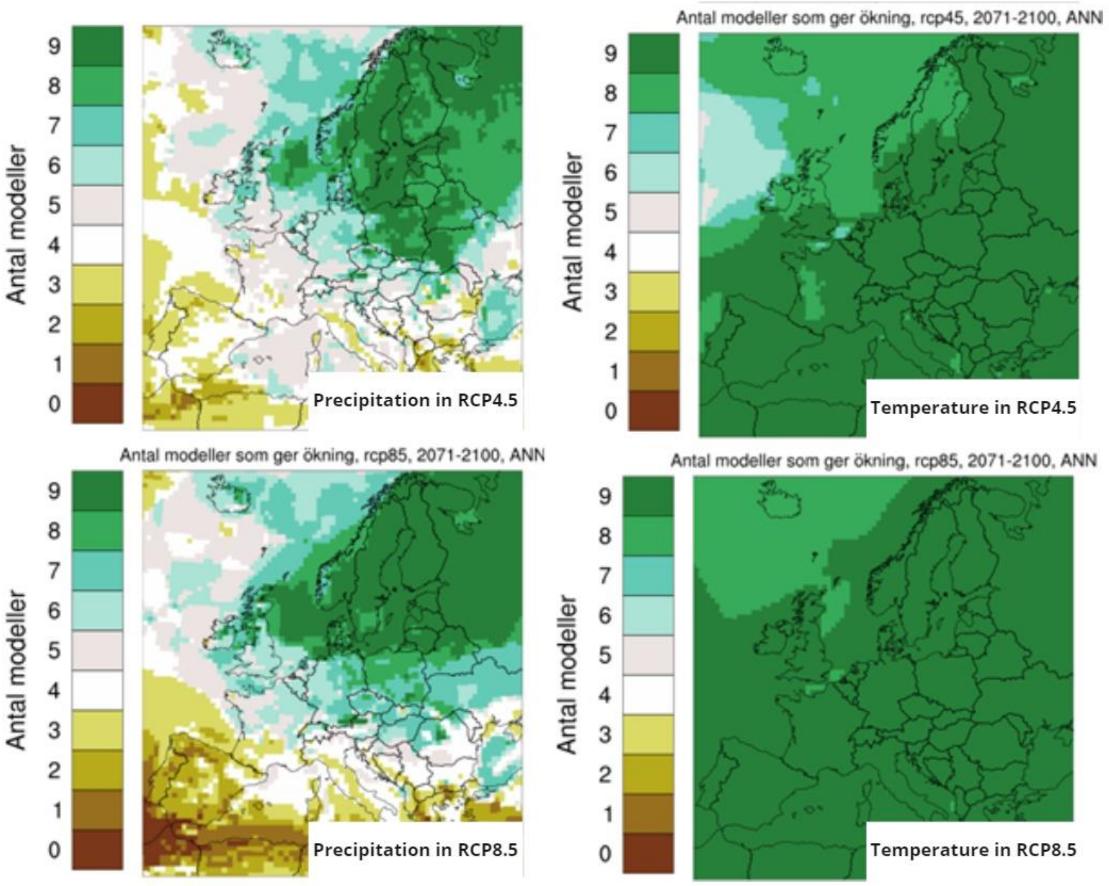


FIGURE 9 THE RELIABILITY OF THE MODEL RESULTS (NUMBER OF CLIMATE SCENARIOS IN THE ENSEMBLE THAT SHOW AN INCREASE FOR THE PERIOD 2071-2100 COMPARED TO THE CONTROL PERIOD 1971-2000)

3.9. URBANIZATION TREND ANALYSIS FOR DUBLIN

Land use/land cover (LULC) changes have big impact on urban runoff since impervious surfaces don't allow natural infiltration and allow accumulation of rainfall, increasing the load in urban drainage systems. In order to tie the impact of runoff reduction using green roofs on the overall runoff volume, urbanization trends in Dublin are analysed through assessment of land use maps in 2006 and 2018. Land use maps are obtained from the Urban Atlas which has a legend depicting urban land use, including low density urban fabric, with a resolution that is 100 times higher than CORINE land cover maps. Urban Atlas is a local component of Copernicus project which is the EU's Earth observation programme and it provides pan-European comparable land cover and land use data covering a number of Functional Urban Areas (Copernicus, 2018) The coordinate reference system used for the global land cover database is ETRS89 Lambert Azimuthal Equal Area CRS ETRS-LAEA EPSG code: 3035. Data is processed with a reclassification in QGIS of the existing land use classes identified in Urban Atlas to simplify the land use change analysis. Twenty land use classes are used which are listed in Figure 21. The maps are clipped in QGIS to only showcase Dublin City urban core and the administrative border map is obtained from Central Statistics Office Ireland (CSO Ireland, 2011). Finally, the shapefile showing all the buildings in Dublin is obtained from Geofabrik to identify the total area of the rooftops (Geofabrik, 2018)

LULC dynamics are analysed in GIS by using Modules for Land Use Change Evaluation (MOLUSCE) in QGIS software (Guidigan et al., 2019). MOLUSCE uses multi-layer perceptron artificial neural network (MLP-ANN) to carry out the change detection. MLP-ANN method is found to be more accurate than the linear regression method (Jogun 2016). The changes between 2006 and 2018 are generated and a class statistics and transition matrix are developed which describe the changes occurred between 2006 and 2018. The transition matrix identifies the changes in the pixels in both maps and create a statistical database. The outputs from the transition matrix is used to make comments on the expected changes in the future period in the city. In order to carry out the analysis in MOLUSCE, variables and drivers like the digital elevation model, distances to roads and streams are used to improve the accuracy of the output in addition to the land use maps. Distance from the main roads and streams maps have been prepared using rasterization from vector maps and carrying out proximity analysis in QGIS. The MOLUSCE neural network learning curve to carry out the MLP-ANN analysis is shown in Figure 10.

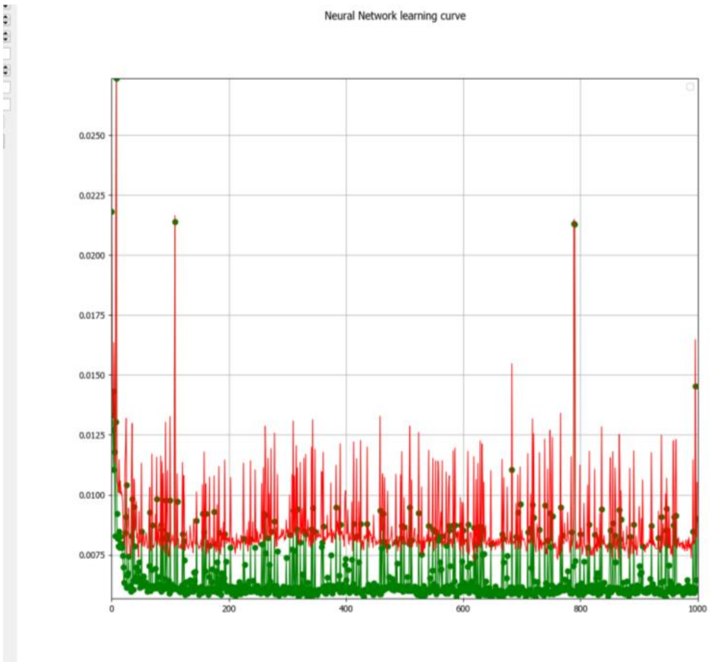


FIGURE 10 NEURAL NETWORK LEARNING CURVE FOR MLP-ANN ANALYSIS IN MOLUSCE

CHAPTER 4 RESULTS AND DISCUSSION

4.1. GREEN ROOF PERFORMANCE UNDER CURRENT METEOROLOGICAL CONDITIONS

The results depicted in this section describing the green roof performance under current meteorological conditions and model validation are taken from the unpublished work of Dr. Bidroha Basu which is elaborated further in the CHAPTER 5 CONCLUSIONS section, mentioning the limitations of this study.

4.2. ANALYSIS OF THE DATA

The data taken from MET Eirann for the time between 1st January 1990 and 29th February 2020 shows %60.23 of the total days were without precipitation while %39.77 were rainy. The average rainfall in days with precipitation is 3.51 mm/day and the maximum precipitation intensity is 26.5 mm/hour. The distribution of rainfall intensity is presented in Table 5 out of a total of 11,017 days.

TABLE 5 RAINFALL INTENSITY DISTRIBUTION BETWEEN 01/01/1990 AND 29/02/2020

RAINFALL INTENSITY	>10 MM	>20 MM	>30 MM	>50 MM
PERCENTAGE	~4.89%	~1.09%	~0.4%	~0.05%
NUMBER OF DAYS	539	120	44	6

The daily maximum temperature ranged between -4.9°C to 28.5°C throughout the year while daily minimum temperature range is -11.5°C to 18.8°C. The mean temperature is 9.26°C with approximately 2.11% days recorded temperatures below 0°C. The relative humidity is recorded between 25-100%, with an average of 82.96%. The average wind speed is 5.43 m/s with the highest wind speed of 23.15 m/s. Average sunshine duration is recorded as around 4.01 hours. The climate of the city can be described as humid, windy with moderate precipitation and relatively low sun exposure and the summer temperature not above 30°C while 7 to 8 days below 0°C in winter period. Figure 11 presents the meteorological data in graph format.

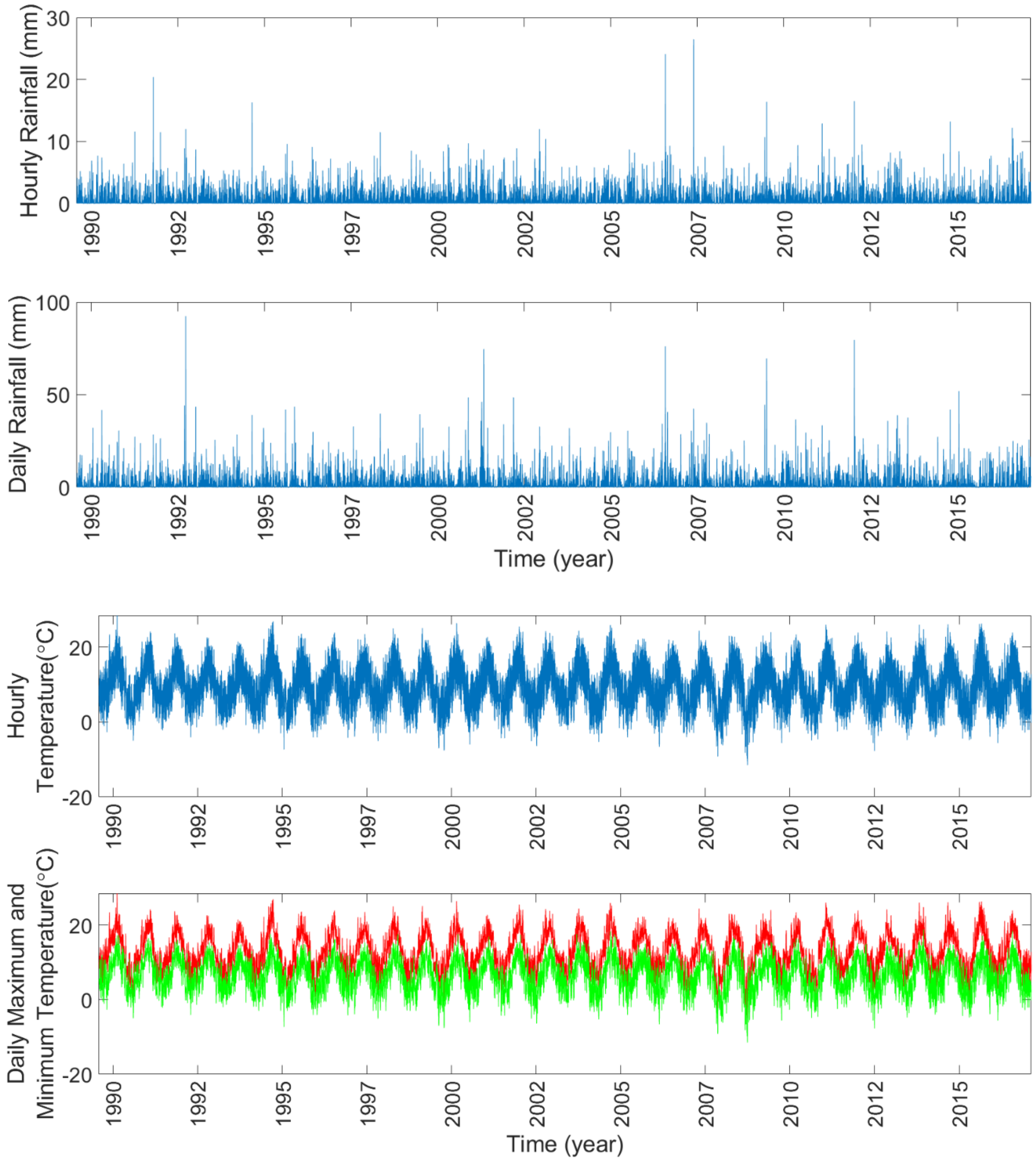


FIGURE 11 HOURLY AND DAILY TIME SERIES PLOTS OF PRECIPITATION, TEMPERATURE, RELATIVE HUMIDITY AND MEAN WIND SPEED

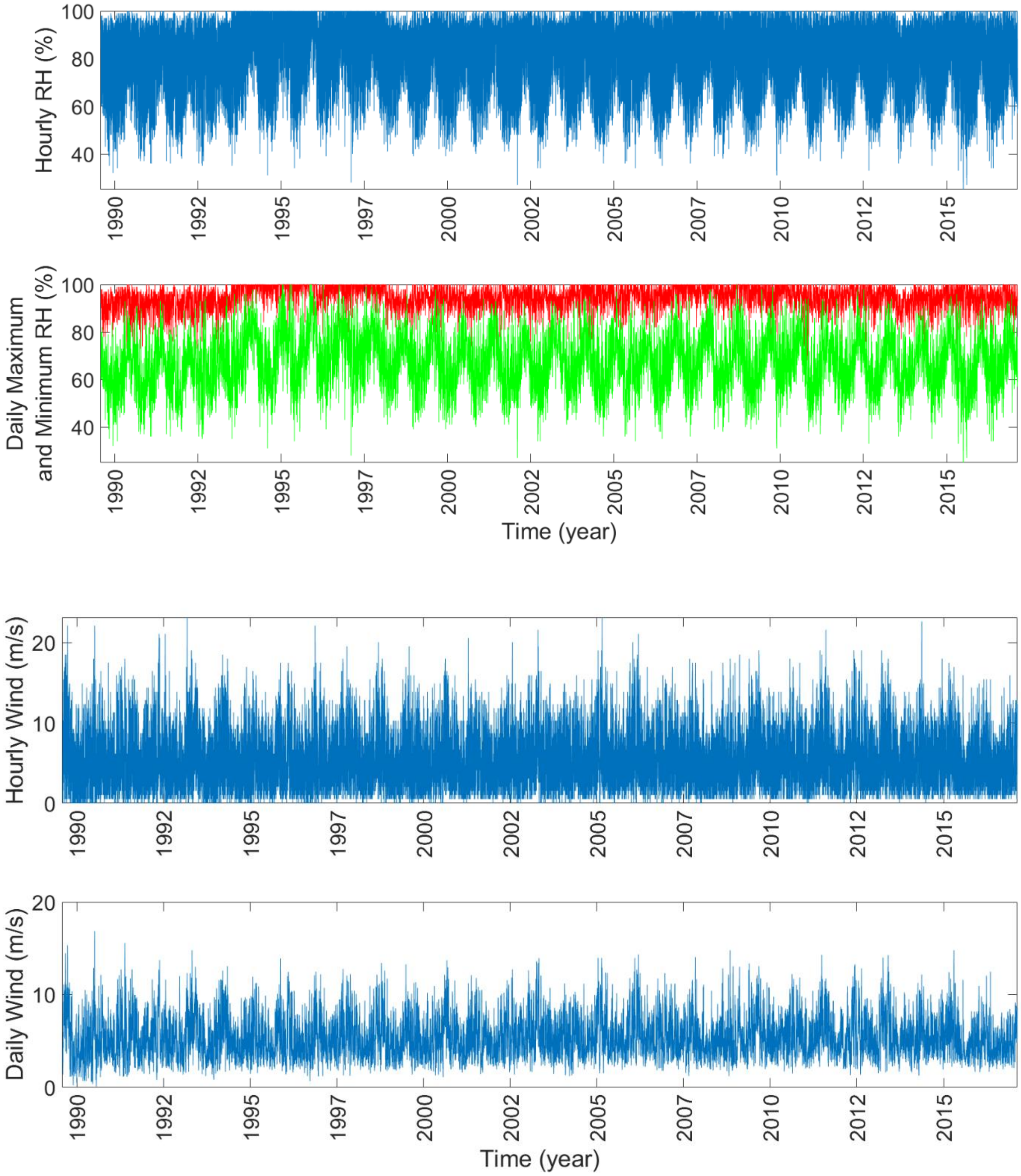


FIGURE 12 HOURLY AND DAILY TIME SERIES PLOTS OF PRECIPITATION, TEMPERATURE, RELATIVE HUMIDITY AND MEAN WIND SPEED

4.3. MODEL VALIDATION RESULTS

The observed runoff and the model results are compared to see how accurate the model is able to simulate the runoff from the green roof. As shown in Figure 13, the model has a slight tendency to overestimate the peak runoff while underestimating the low runoff. The difference in the compared values are low and the values of statistical measures to indicate the validation are significantly close together, indicating the model is able to simulate runoff close to reality. The NSE, CORR and KGE are calculated as 0.961, 0.999 and 0.806 respectively. Figure 13 shows the changes in the weight of the vegetated beds which is used to calculate runoff and the comparison between the observed runoff and the simulation. As mentioned, the observation could only take place for 8 consecutive days after which, COVID-19 restrictions prevented the measurements.

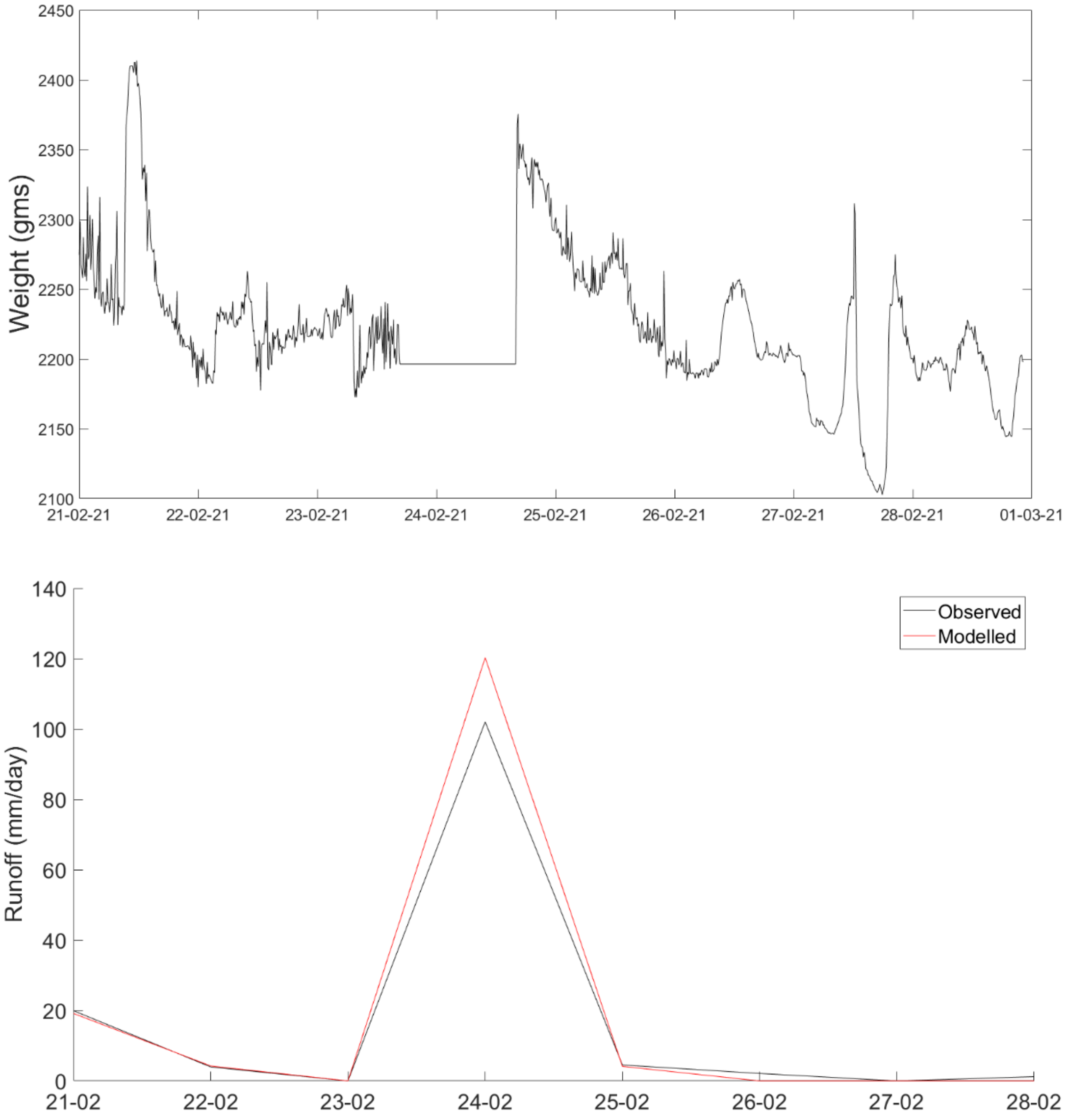


FIGURE 13 MASS OF THE VEGETATED BED IN GRAMS (TOP), COMPARISON BETWEEN THE ACTUAL RUNOFF FROM THE VEGETATED BED AND THE SIMULATED RUNOFF (BOTTOM)

4.4. GREEN ROOF PERFORMANCE WITH OBSERVED DATA

The analysis for estimating the runoff reduction capacity of the green roof through the model simulation is carried out for eight scenarios as mentioned considering the vegetation is sedum, strawberries, cotton and mint and for two different substrate depths, 80 mm and 150 mm. The results are classified to show performance under rainfall intensities greater than 10 mm, 20 mm, 30 mm and 50 mm. The obtained results are shown in Table 6.

TABLE 6 RUNOFF REDUCTION RATE WITH A GREEN ROOF WITH DIFFERENT SUBSTRATE DEPTH AND VEGETATION UNDER OBSERVED HISTORICAL CLIMATE CONDITIONS

PRECIPITATION			> 50 MM	> 30 MM	> 20 MM	> 10 MM
NUMBER OF DAYS		Crop Coefficient	6	44	120	539
SHALLOW SUBSTRATE 80MM	Sedum	1.0	12.10	23.94	32.77	55.09
	Strawberries	0.75	11.01	21.87	29.97	51.40
	Cotton	0.5	9.80	19.96	27.12	47.61
	Mint	1.1	12.53	24.80	33.92	56.57
MEDIUM SUBSTRATE 150MM	Sedum	1.0	24.31	47.38	60.48	77.21
	Strawberries	0.75	22.68	44.69	57.41	74.57
	Cotton	0.5	20.64	42.27	54.51	71.87
	Mint	1.1	24.91	48.60	61.75	78.21

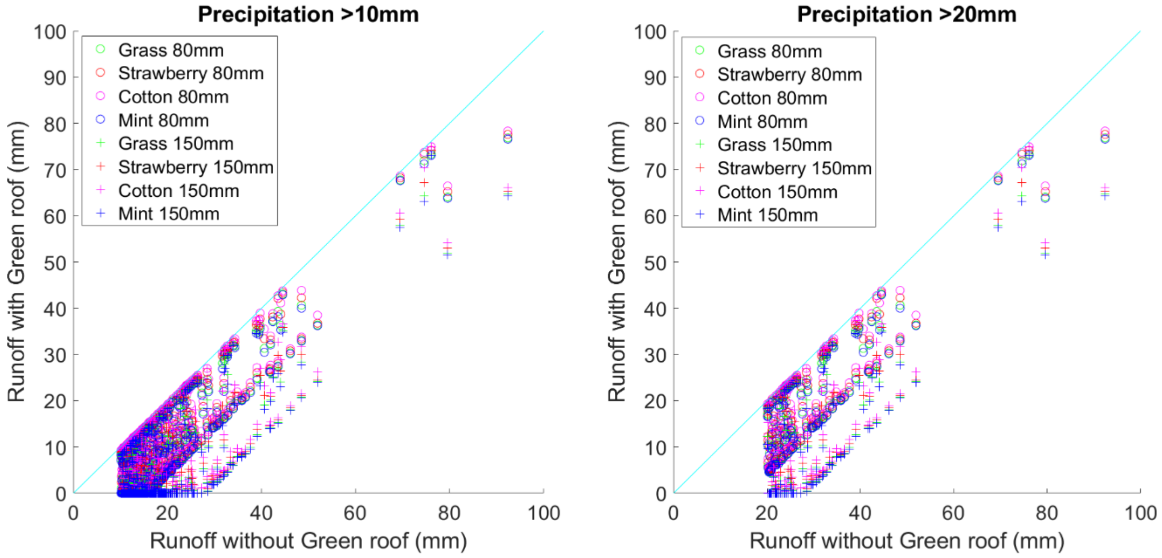
The results show 150 mm substrate depth performs better in reducing runoff, in line with the findings from literature. As the soil depth increases, the substrate is able to collect and store more water. Runoff can only be generated when the green roofs is saturated or at its field capacity, hence the recharge capacity of the roof's runoff retention performance depend on substrate's drying rate in between rain events (Bengtsson et al., 2005).

Regarding the vegetation, mint is the most effective in reducing runoff as it has the highest crop coefficient hence the evapotranspiration capacity. Plants' water usage relies on evapotranspiration and transpiration, transpiration being negligible in general as the water uptake can be less than 1%, but evapotranspiration has a significant impact on water usage (Vijayaraghavan et al., 2014). Crop coefficient is an effort to standardize evapotranspiration and use it for scheduling irrigation in agriculture. It is calculated by using weather conditions, crop types, irrigation schemes and field management in agriculture so it can be used to estimate water uptake due to evapotranspiration in green roof setting as well (Allen et al., 1998). Mint is followed by sedum, strawberries and finally cotton in terms of performance, related with their crop coefficients.

As for the varying rainfall intensities, the results conclude that the as the rainfall intensity increases, the percentage of runoff reduction decreases which aligns with the literature. During rainfall events with lower intensity, it can be said that the majority of the rainfall is stored in the substrate, increasing the soil moisture content and then consumed during evapotranspiration. On the contrary, during high intensity rain events, the soil moisture increases rapidly and may stay saturated, diminishing the water storage capacity to minimum or non-existent, hence leading to more runoff. This is also validated as the deeper substrate, results in a higher rate of runoff reduction (%78.21 for mint in events greater than 50 mm) than the shallow substrate layer (%56.57 for the same). This relates to the increasing soil volume leading to higher soil moisture content limit in the green roof (Kasmin et al., 2010; Carbone et al., 2014; Vijayaraghavan; 2014). After the water holding capacity is reached though, stored water eventually contributes to the runoff, for deeper substrates, this happens slower (Vijayaraghavan; 2014). The difference between mint and sedum is fairly marginal for higher intensity rainfall events (%12.53 and %12.10 in 50 mm rainfall, shallow substrate) but for lower intensity events, the difference in performance increases and mint performs better (%53.57 and %55.09). This shows the increased evapotranspiration when the amount of captured water is low enough to allow regeneration of the green roof and the stored water to be used up for plant uptake and evapotranspiration (Bengtsson, 2005)

The runoff performance with and without the green roof in the same weather and soil conditions is compared and presented in

Figure 14. The runoff from the green roof is represented in the vertical axis while runoff without the green roof is shown in the horizontal axis. The points in graphs represent the daily runoff simulated in the model. The cyan colored line shows the neutrality where the runoff would be the same with or without the green roof, meaning the points under the line are indicating there is runoff reduction due to the existence of the green roof.



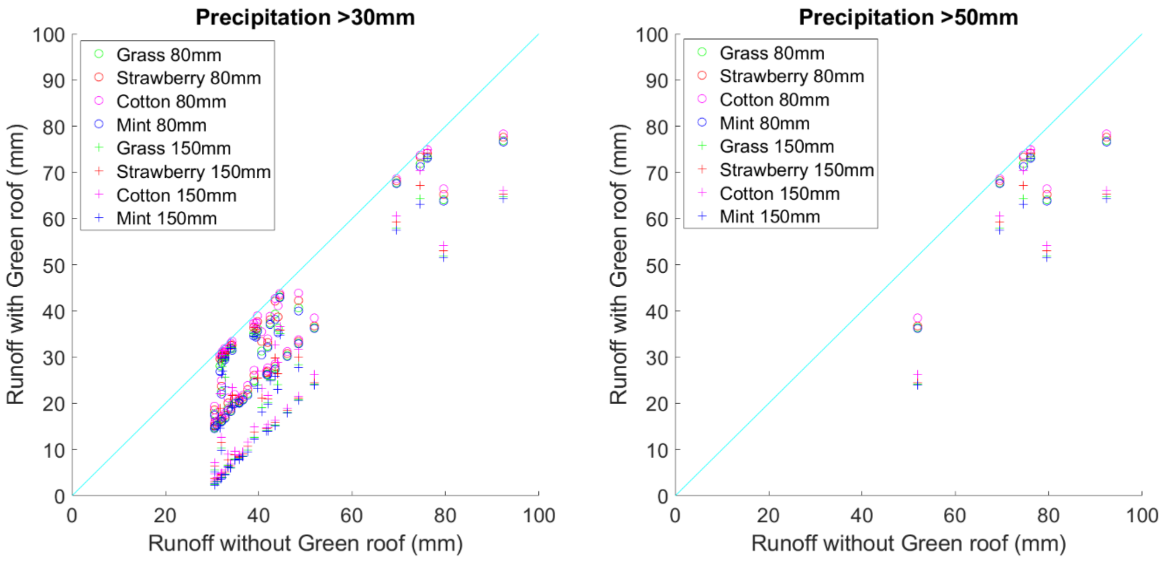


FIGURE 14 RUNOFF WITH AND WITHOUT THE GREEN ROOF

4.5. GREEN ROOF PERFORMANCE WITH CLIMATE CHANGE PROJECTION

The results depicted in this section describing the green roof performance with climate change projection including bias correction are original to this study.

4.6. ANALYSIS OF THE DATA

The data is taken from SMHI for the time between 29th February 2020 and 31st December 2100 for both RCP4.5 and RCP8.5 scenarios. For RCP4.5; %12.4 of the total days were without precipitation while %87.6 were rainy. The average rainfall in days with precipitation is 4.37 mm/day. As for the RCP8.5, %23.4 of the total days were without precipitation while %76.6 were rainy. The average rainfall in days with precipitation is 3.69 mm/day.

The distribution of rainfall intensity is presented in Table 5 out of a total of 29,525 days in the future period.

TABLE 7 RAINFALL INTENSITY DISTRIBUTION BETWEEN 01/01/1990 AND 29/02/2020

SCENARIO	RAINFALL INTENSITY	>10 MM	>20 MM	>30 MM	>50 MM
RCP4.5	Percentage	~10.04%	~2.28%	~0.65%	~0.03%
	Number of days	2964	672	191	9
RCP8.5	Percentage	~7.58%	~2.02%	~0.97%	~0.24%
	Number of days	2236	597	285	72

RCP8.5 scenario exhibits higher probability of extreme events then the RCP4.5 scenario while lower intensity rainfall events are lower in number in line with the IPCC report (Kovats et al., 2014). There is more inclination for rainfall events with greater intensity than 20 and 30mm in RCP8.5 then RCP4.5 as well.

The projection data clearly has bias for overestimating precipitation and simulate more rainy days both in RCP4.5 and RCP8.5, as the number of rainy days is extremely high. The data would benefit bias correction however since the input variables are numerous, bias correcting them would lead to significant errors in the output. So, bias correction on the output runoff data is carried out to compensate the over or under estimation. Figure 15 and Figure 16 presents the time series plot of the precipitation which also shows the historic data is significantly higher than the observed precipitation data taken from the Dublin Airport weather station.

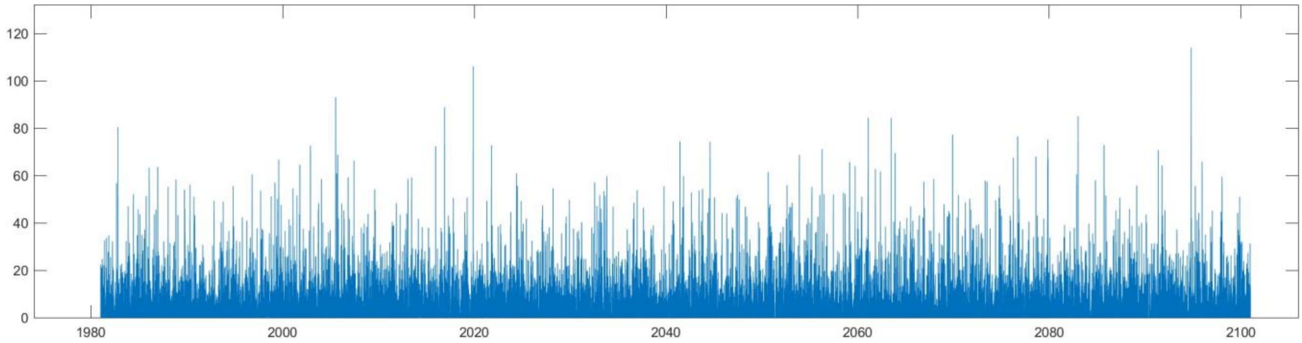


FIGURE 15 PRECIPITATION IN RCP4.5 BETWEEN 01/01/1981 AND 31/12/2100

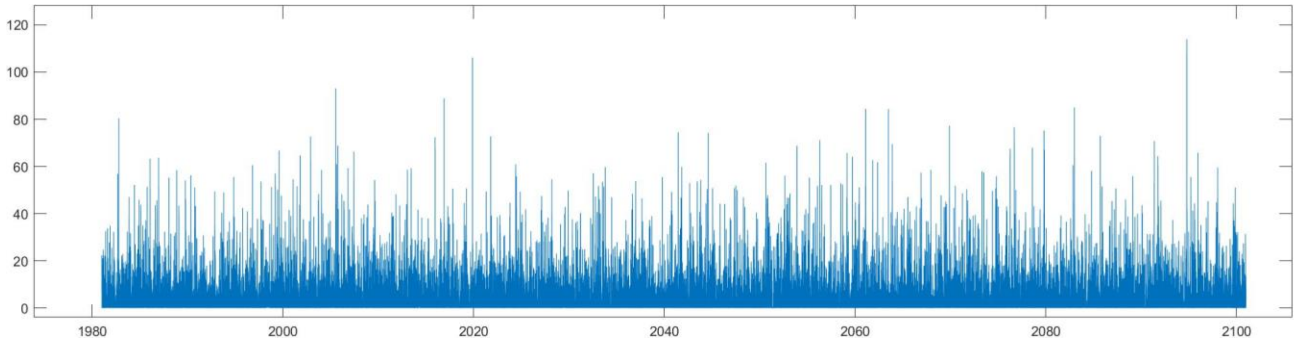


FIGURE 16 PRECIPITATION IN RCP8.5 BETWEEN 01/01/1981 AND 31/12/2100

4.7. SCENARIO RCP 4.5

For the scenario projection, 80mm substrate depth is chosen for the simulation. The model results for runoff reduction in RCP4.5 scenario is consistent with the findings for the simulation based on the actual historical data taken from MET Eirann. The existence of green roof allows a significant reduction in runoff in future projection for precipitation. Even with very high rainfall green roof is able to capture some amount of water. For rainfall events greater than 10mm precipitation, the runoff reductions are %61.18, %56.20, %50.98, %63.11 for grass, strawberry, cotton and mint respectively while for events with intensity greater than 50mm, the reduction is %8.16, %6.07, %3.84, %8.96 respectively as shown in Table 8.

The performance decreases significantly for rain intensities greater than 50mm since have higher intensities. Table 8 summarizes the findings of the simulation using the climate change projection data. High rainfall intensity leads to higher runoff since the soil moisture content is reached very quickly, creating direct runoff from the green roof (Shafique et al., 2018).

RAINFALL INTENSITY / PERCENTAGE OF RUNOFF REDUCTION		RUNOFF REDUCTION PERFORMANCE (%)
>10MM RAIN	Grass	61.18
	Strawberry	56.20
	Cotton	50.98
	Mint	63.11
>20MM RAIN	Grass	43.99
	Strawberry	39.52
	Cotton	34.96
	Mint	45.77
>30MM RAIN	Grass	31.49
	Strawberry	27.85
	Cotton	24.12
	Mint	32.93
>50MM RAIN	Grass	8.16
	Strawberry	6.07
	Cotton	3.84
	Mint	8.96

TABLE 8 RUNOFF REDUCTION WITH GREEN ROOF IN RCP4.5 SCENARIO

Similarly, since the climate change model estimates a higher frequency in the rain events, the green roof is not able to dry out in between events which causes the soil moisture content remain high. High soil moisture content leads to decrease in water capture capacity, hence more runoff (Vijayaraghavan et al., 2014).

The runoff performance with and without the green roof in the same weather and soil conditions is compared and presented in Figure 17. Again, the data points under the cyan line represent the runoff reduction achieved due to the existence of the green roof. The figures show, mint has the best performance while cotton has the worst in reducing runoff for each rainfall intensity ranges.

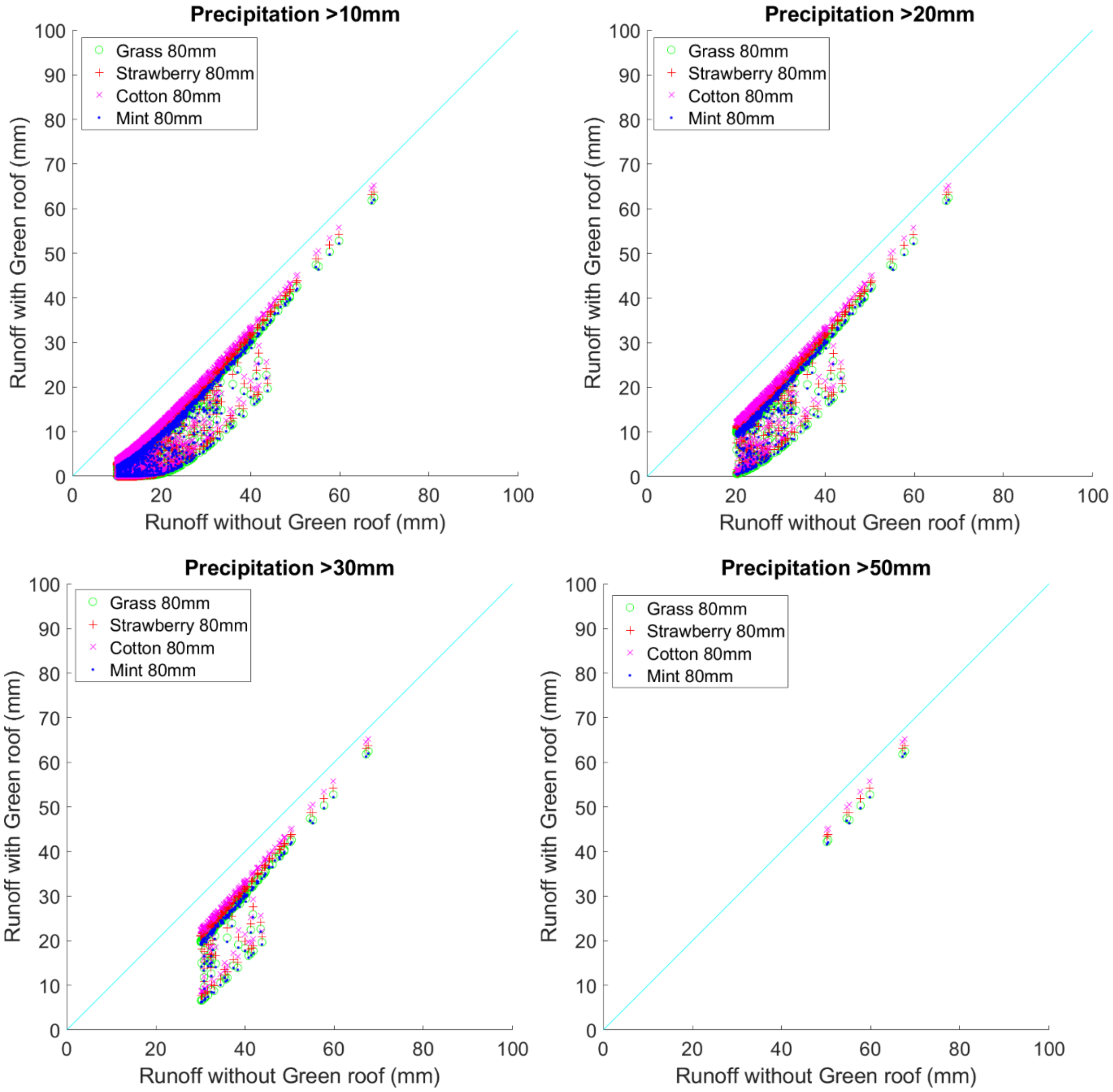


FIGURE 17 RUNOFF WITH AND WITHOUT THE GREEN ROOF IN RCP4.5 SCENARIO

4.8. SCENARIO RCP 8.5

80mm substrate depth is chosen for RCP8.5 scenario as well.. The model results for runoff reduction in RCP8.5 scenario is consistent with the findings for the simulation based on the observed data and the RCP4.5 scenario. The existence of green roof allows a significant reduction in runoff in even though the rainfall intensity and frequency is higher in RCP8.5 compared to RCP4.5. For rainfall events greater than 10mm precipitation, the runoff reductions are %53.01, %47.77, %42.44, %55.08 for grass, strawberry, cotton and mint respectively while for events with intensity greater than 50mm, the reduction is %31.71, %28.96, %26.22, %32.81 respectively as shown in Table 9.

TABLE 9 Runoff Reduction With Green Roof In RCP8.5 Scenario

RAINFALL INTENSITY / PERCENTAGE OF RUNOFF REDUCTION		RUNOFF REDUCTION (%)
>10MM RAIN	Grass	53.01
	Strawberry	47.77
	Cotton	42.44
	Mint	55.08
>20MM RAIN	Grass	43.20
	Strawberry	39.01
	Cotton	34.84
	Mint	44.88
>30MM RAIN	Grass	37.39
	Strawberry	33.93
	Cotton	30.49
	Mint	38.79
>50MM RAIN	Grass	31.71
	Strawberry	28.96
	Cotton	26.22
	Mint	32.81

The difference between runoff performance for rainfall intensities higher than 50mm between RCP4.5 and RCP8.5 (for grass: %8.16 in RCP4.5 and %31.71 in RCP8.5) can be explained with the nature of the selected bias correction method which is explained further in section 4.9 Effects of Bias Correction.

The runoff reduction performance decreased compared to RCP4.5 scenario since the rainfall intensity, amount and frequency are higher in RCP8.5 than RCP4.5. Green roof is less able to retain runoff due to field capacity being reached quicker and there is less time in between rainfall events to allow the green roof to dry out and regenerate. However, even in rainfall intensities greater than 50mm, there is approximately 10-20mm runoff reduction difference between cases with and without the green roof. The highest runoff without the green roof is approximately 90 mm while with the green roof runoff is calculated as 65mm.

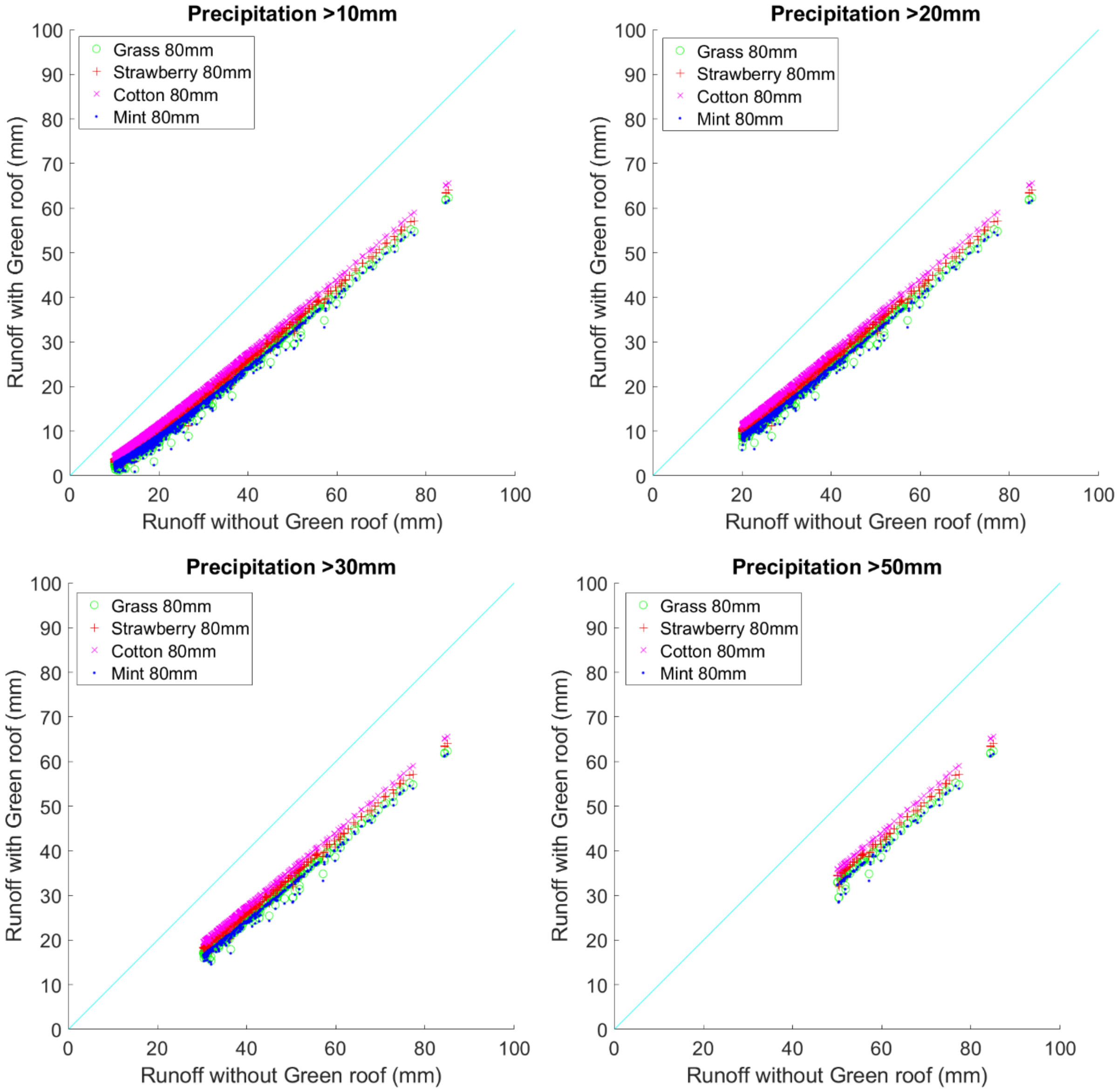


FIGURE 18 RUNOFF WITH AND WITHOUT THE GREEN ROOF IN RCP8.5 SCENARIO

4.9. EFFECTS OF BIAS CORRECTION

In order to clearly see the impact of bias correction on the results, the analysis is carried out both with and without bias correction. Figure 19 shows the runoff with rainfall intensity higher than 10mm with and without bias correction. It can be concluded that without bias correction, the values are significantly underestimated hence the runoff reduction with the green roof is extremely low. After correcting the results using the outputs from the model that uses the observed weather parameters, the runoff reduction is closer to the observed values, making the results more realistic.

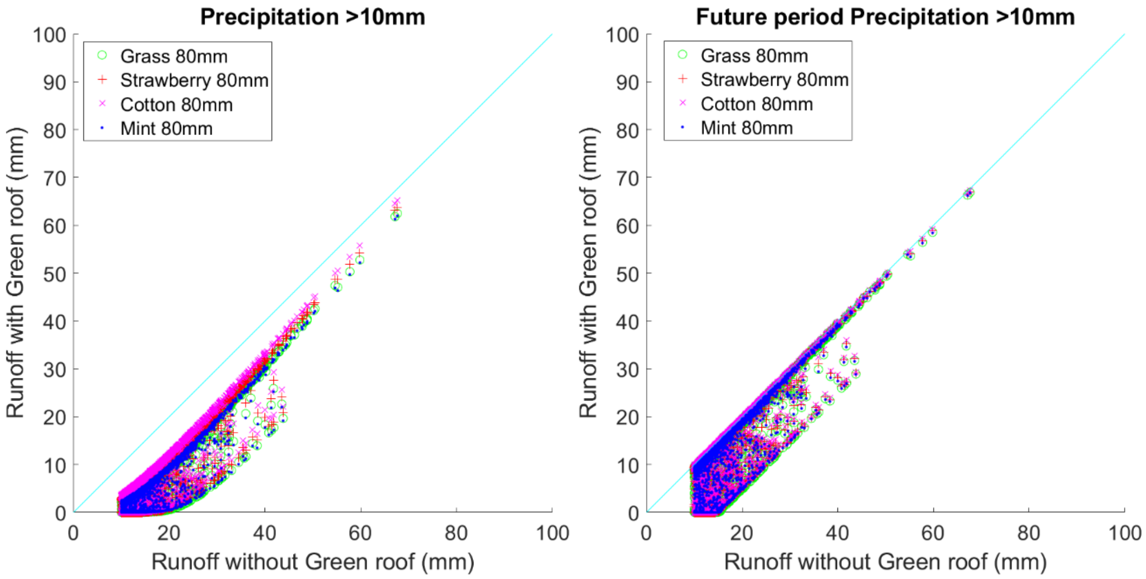


FIGURE 19 RUNOFF WITH AND WITHOUT GREEN ROOF WITH INTENSITY GREATER THAN 10MM WITH BIAS CORRECTION (LEFT) WITHOUT BIAS CORRECTION (RIGHT)

This bias correction method which uses CDF to calculate the runoff, tends to underestimate results in the lower quantiles in the model while overestimating them on the high quantiles. This tendency can be clearly seen in the graph provided by Li et al., given in Figure 8. A similar graph is developed for the CDF and runoff relationship between the observed data and the modelled data in this study as shown in Figure 20 which presents the lower quantiles of both models. The graph indicates both lines (observed and modelled) intercept each other at one point, proving that underestimation in lower quantiles and overestimation in higher quantiles are happening here as well. The difference between the runoff performance for rainfall intensities greater than 50mm in RCP4.5 and RCP8.5 can be explained by this phenomena. Since the rainfall intensity is significantly higher in RCP8.5 the results are placed in much higher quantiles in RCP8.5 scenario than in the RCP4.5. Increasing the quantile directly leads to higher overestimation which creates seemingly “better” runoff reduction performance in the results in RCP8.5 than in RCP4.5. This is consistent with Li et al.’s study where they indicate the model exhibits higher variance at the tails of distribution though this method significantly reduces these differences (Li et al., 2010). The bias correction can be further improved with the usage of actual observed runoff data registered for a long period rather than using the produced model which uses the observed weather parameters to estimate the runoff like in this study.

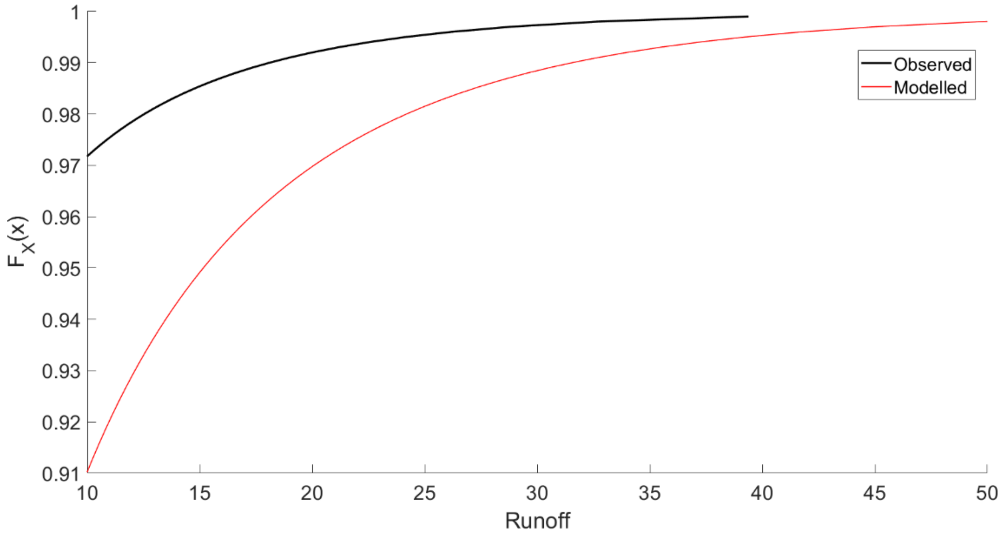


FIGURE 20 CDF GRAPH OF THE OBSERVED (BLACK) AND MODELLED (RED) RUNOFF

4.10. POTENTIAL FOR SUSTAINABLE STORMWATER MANAGEMENT

As seen, climate change being an anthropological phenomena can have impact on the frequency and the degree of rainfall events and consequently, flooding. The high probability for increased precipitation and flooding is expected to be more and more frequent (IPCC, 2019). Rainfall intensity is expected to increase especially in mid and high latitudes like Europe and Dublin (Meehl et al., 2005). This study shows green roofs can be used to mitigate the flooding risk amplified by climate change and urbanization, supporting many studies in the same field. Liu showed green roofs can be most effective in reducing runoff and peak flow in a 2 year frequency event and while a decrease in performance can be observed in 10 and 100 years frequency events, the runoff reduction can be still significant, between 28-82% (Liu et al., 2020). Similar to this study, building scale runoff experiments and models showed green roof performance depend on several factors like climatic conditions, seasonality, antecedent dry periods, substrate depth and type and rainfall intensity (Bengtsson et al., 2005; Carter et al., 2006; Mentens et al., 2006; Villareal, 2007; Berndtsson, 2010; Carson et al., 2013; Fassman-Beck et al., 2013) and modelling/simulation approach can help with the optimum design of green roofs for storm water management. Several catchment scale studies prove green roof impact on runoff reduction can be significant in the urban scale similar to building scale. By simulating the urban catchment scale based on the observed runoff from one building rooftop, it is possible to envision the impact of retrofitted roofs on the urban drainage system. Berthier developed a model to be used as a tool for green roof design, that estimates hydrological patterns of green roofs under different rainfall events (Berthier et al., 2011). Similarly, Versini developed a model in SWMM to simulate green roof runoff both in building and catchment scale and concluded green roofs are efficient in reducing runoff both in building and catchment scale. At catchment scale, the impact is highly dependent on the potential for retrofitting the roofs but Versini suggested 20% retrofit leads to 20-35% reduction in catchment scale while 10-100% reduction in building scale. It is also noted that building scale runoff and basin scale runoff is compared using multi-linear regression method and found out to be a fairly reliable, although rough, method to estimate basin scale runoff based on building scale data. Since observations and analysis in building scale, such as the methods used in this study as well, are more easy to carry out, further analysis on catchment scale impacts can be done with elaborate variations in the model calculation (Versini et al., 2015).

4.11. LULC CHANGES IN DUBLIN

Land use maps for 2006 and 2018 are presented in Figure 22 according to the administrative boundary of Dublin. Land use distributions are shown in Figure 23 and Figure 24. It can be seen the area surrounding the city core mainly consist of agricultural and semi natural areas followed by discontinuous dense urban fabric and industrial, commercial, public, military, private units both in 2006 and 2018. Table 10 summarizes the calculated changes between the land use classes for the period between 2006 and 2018 while Figure 25 visualizes the transition between the land use classes.

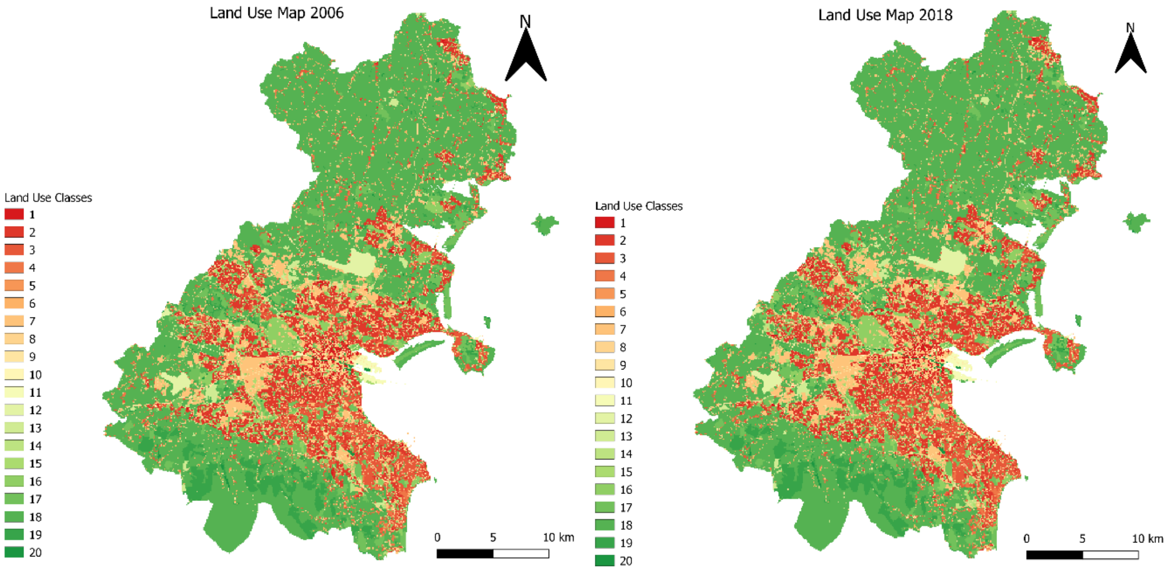


FIGURE 22 LAND USE MAPS FOR 2006 AND 2018

1. Continuous Urban Fabric (Sealing Degree > 80%)
2. Discontinuous Dense Urban Fabric (Sealing Degree 50% - 80%)
3. Discontinuous Medium Density Urban Fabric (Sealing Degree 30% - 50%)
4. Discontinuous Low Density Urban Fabric (Sealing Degree 10% - 30%)
5. Discontinuous Very Low Density Urban Fabric (Sealing Degree < 10%)
6. Isolated Structures
7. Industrial, commercial, public, military and private units
8. Fast transit roads and associated land
9. Other roads and associated land
10. Railways and associated land
11. Port areas
12. Airports
13. Mineral extraction and dump sites
14. Construction sites
15. Land without current use
16. Green urban areas
17. Sports and leisure facilities
18. Agricultural + Semi-natural areas
19. Forests
20. Water

FIGURE 21 LAND USE CLASSES

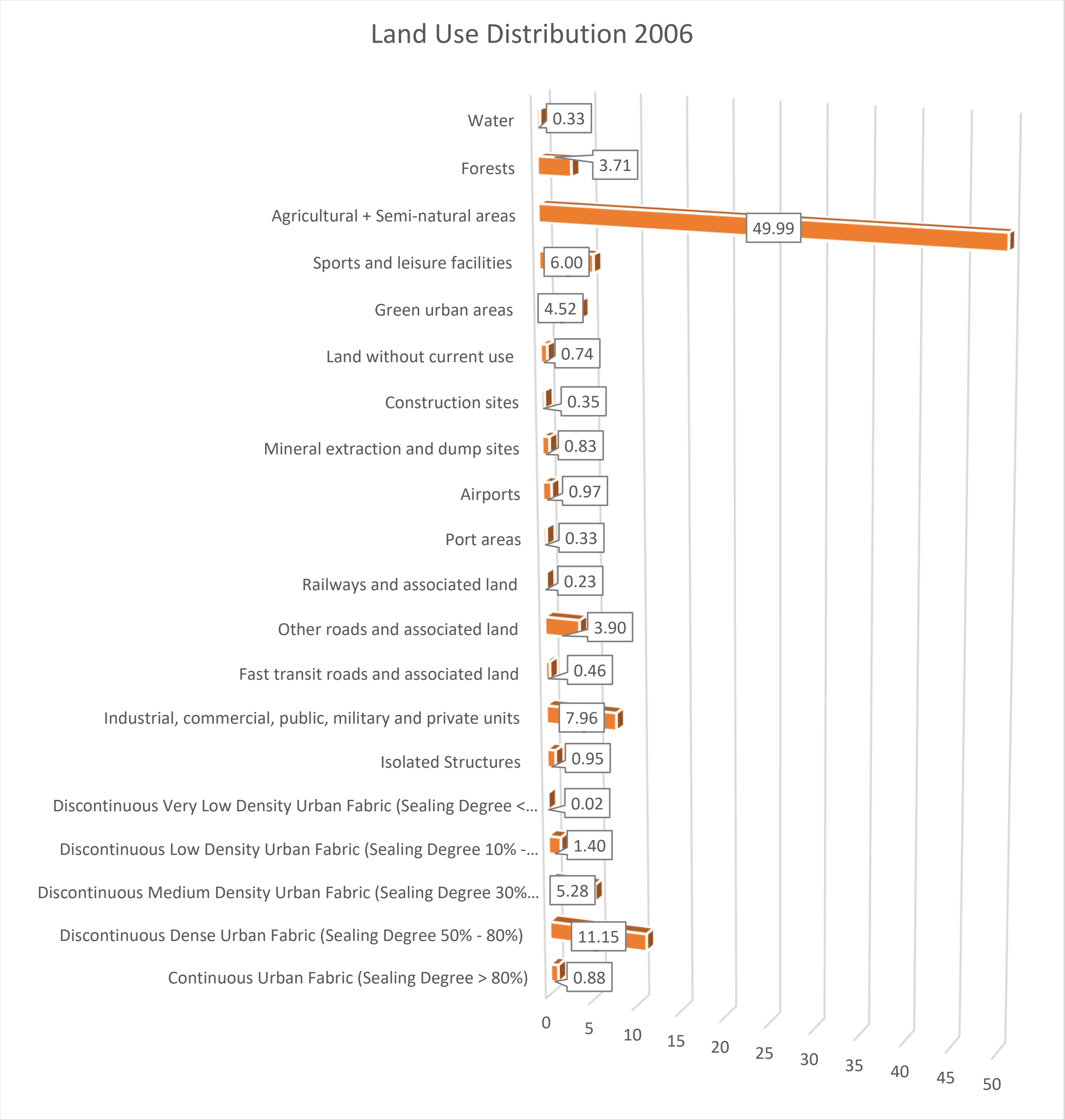


FIGURE 23 LAND USE DISTRIBUTION IN 2006

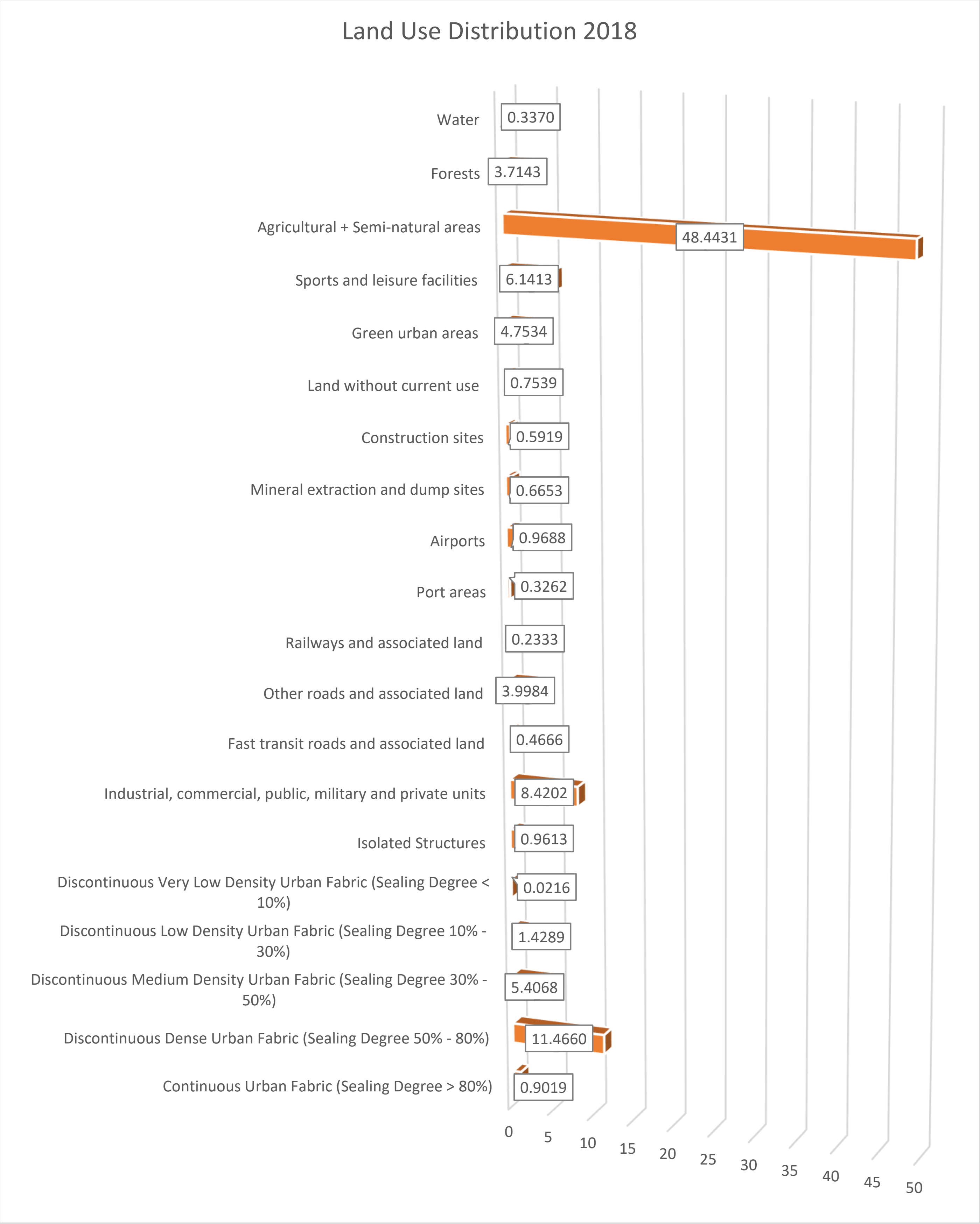


FIGURE 24 LAND USE DISTRIBUTION IN 2018

TABLE 10 LAND USE CHANGE STATISTICS

URBAN ATLAS LAND USE CLASSES	2006	2018	Δ	2006%	2018%	Δ %
AGRICULTURAL + SEMI-NATURAL AREAS	462.86 sq. km.	448.52 sq. km.	-14.34 sq. km.	49.992	48.443	-1.549
AIRPORTS	8.97 sq. km.	8.97 sq. km.	0.00 sq. km.	0.969	0.969	0.000
CONSTRUCTION SITES	3.25 sq. km.	5.48 sq. km.	2.23 sq. km.	0.351	0.592	0.241
CONTINUOUS URBAN FABRIC (SEALING DEGREE > 80%)	8.17 sq. km.	8.35 sq. km.	0.18 sq. km.	0.882	0.902	0.019
DISCONTINUOUS DENSE URBAN FABRIC (SEALING DEGREE 50% - 80%)	103.19 sq. km.	106.16 sq. km.	2.97 sq. km.	11.145	11.466	0.321
DISCONTINUOUS LOW DENSITY URBAN FABRIC (SEALING DEGREE 10% - 30%)	12.99 sq. km.	13.23 sq. km.	0.24 sq. km.	1.403	1.429	0.026
DISCONTINUOUS MEDIUM DENSITY URBAN FABRIC (SEALING DEGREE 30% - 50%)	48.91 sq. km.	50.06 sq. km.	1.15 sq. km.	5.283	5.407	0.124
DISCONTINUOUS VERY LOW DENSITY URBAN FABRIC (SEALING DEGREE < 10%)	0.16 sq. km.	0.20 sq. km.	0.04 sq. km.	0.017	0.022	0.004
FAST TRANSIT ROADS AND ASSOCIATED LAND	4.27 sq. km.	4.32 sq. km.	0.05 sq. km.	0.461	0.467	0.005
FORESTS	34.36 sq. km.	34.39 sq. km.	0.03 sq. km.	3.711	3.714	0.003
GREEN URBAN AREAS	41.83 sq. km.	44.01 sq. km.	2.18 sq. km.	4.518	4.753	0.235
INDUSTRIAL, COMMERCIAL, PUBLIC, MILITARY AND PRIVATE UNITS	73.66 sq. km.	77.96 sq. km.	4.30 sq. km.	7.956	8.420	0.464
ISOLATED STRUCTURES	8.81 sq. km.	8.90 sq. km.	0.09 sq. km.	0.952	0.961	0.010
LAND WITHOUT CURRENT USE	6.82 sq. km.	6.98 sq. km.	0.16 sq. km.	0.737	0.754	0.017
MINERAL EXTRACTION AND DUMP SITES	7.64 sq. km.	6.16 sq. km.	-1.48 sq. km.	0.825	0.665	-0.160
OTHER ROADS AND ASSOCIATED LAND	36.11 sq. km.	37.02 sq. km.	0.91 sq. km.	3.900	3.998	0.098
PORT AREAS	3.06 sq. km.	3.02 sq. km.	-0.04 sq. km.	0.330	0.326	-0.004
RAILWAYS AND ASSOCIATED LAND	2.14 sq. km.	2.16 sq. km.	0.02 sq. km.	0.231	0.233	0.002
SPORTS AND LEISURE FACILITIES	55.58 sq. km.	56.86 sq. km.	1.28 sq. km.	6.003	6.141	0.138
WATER	3.09 sq. km.	3.12 sq. km.	0.03 sq. km.	0.334	0.337	0.003

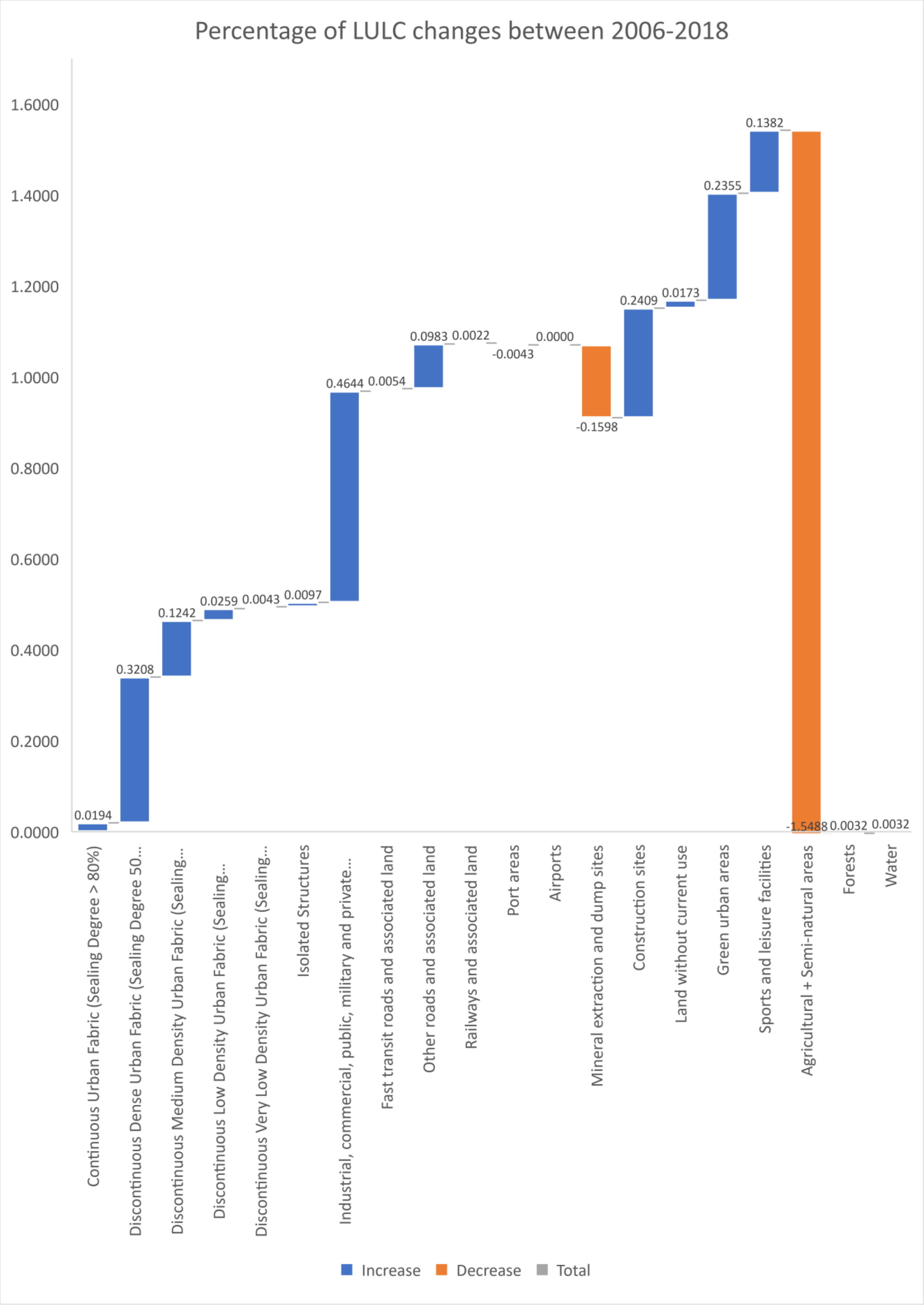


FIGURE 25 LULC CHANGES BETWEEN 2006 AND 2018

The major change in the land use classes are between agricultural and semi natural areas and discontinuous urban dense fabric and commercial areas. This trend shows the urban expansion is occurring at the expense of agricultural areas. Increasing urban fabric (+%1.3) and decreasing agricultural and semi-natural areas (-%1.55) are significant changes as well as even though it is small, increasing urban green areas (+%0.24). The urbanization trend in Ireland is quite significant compared to other European countries, identified as having an annual growth rate of 3.1% between 1990 and 2012, and 2.5% between 2000-2012 while the average rate is 1.4% and 1.1% in European countries respectively for the mentioned time periods (Ahrens, 2019). The increase in discontinuous urban fabric points at urban sprawl since the expansion of continuous urban fabric is rather small. Still, this expansion is significant in terms of stormwater management and urban runoff since the mentioned discontinuous urban fabric classes has a sealing degree of 50-80%, meaning it has high imperviousness. The increasing imperviousness has significant impact on evapotranspiration (Rim, 2009) and decrease or inhibit infiltration all together, change natural flow routes and runoff quality as well as creating fast peak discharges (Jennings et al., 2002; Dougherty et al., 2004; Scalenghe et al., 2009; Verbeiren et al., 2012).

Sprawl creates issues other than increasing imperviousness as well with adverse effects on costs of environmental services provision and the environment (Carruthers et al., 2003). Afforestation seems low considering the changes between 2006 and 2018 which is in line with the literature stating that afforestation is slowed down after 2006 while it is compensated with deforestation (Ahrens, 2019). Ahrens also concluded that de-urbanization is occurring very rarely which can be reflected in the findings in Figure 25, showing unified increase in all urban land use classes. So, even though the urbanization is slowed down since the 1990s, the transformation rate is still high and it is possible to say the transformation of green areas to urban areas are unlikely to be reserved. Since the imperviousness is increasing with the increasing urbanization, implications for flooding is more significant with this scenario, considering RCP4.5 and RCP8.5 cases. The Irish Planning Framework 2040 intends to enhance more compact development and reduction in land use changes through brownfield development within the existing urban fabric. The identified goals for flood risk management include the integration of sustainable urban drainage solutions such as green roofs to break the imperviousness in the city. (NPF, 2019). The total area of building rooftops is calculated using QGIS with the map presented in Figure 26, and found to be 48.25 km^2. Based on the findings in the model simulation, even a 10% of retrofitting the buildings with green roofs would allow a significant reduction in urban runoff, both relieving the pressure in drainage systems and reducing the risk of flooding, especially combined with other type of sustainable urban drainage systems. The model in this study can be a tool for planners and policy makers as well as practitioners to estimate the effects of hypothetical/planned/existing green roofs on the stormwater management systems in reducing urban runoff in urban environment.

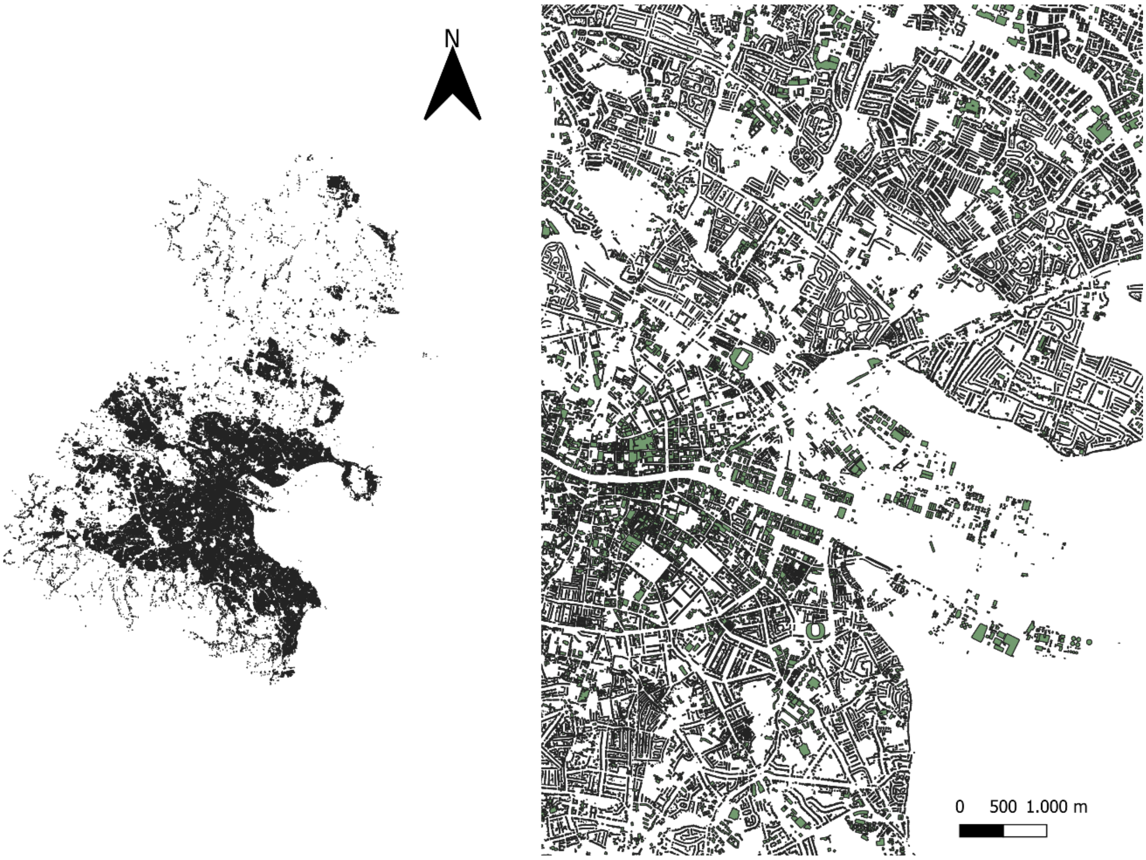


FIGURE 26 BUILDINGS IN DUBLIN

CHAPTER 5 CONCLUSIONS

Climate change is leading to more frequent extreme events. The observed land surface air temperature has already risen by 1.53 °C, affecting hydrological cycles in many regions including Dublin. Rainfall events are expected to increase 7% per degree of warming in the future. The climate shift is in a positive feedback loop with urbanization trends as well. Increasing impervious land cover due to urbanization especially hinders natural hydrological cycle in cities, limiting natural runoff reduction, creating urban floods.

Researchers established climate change scenarios according to radiative forcing based on anthropological activities. Climate change projections are invaluable tools to understand the future effects of climate change for mitigating and adapting to the shift. Hydrological models depicting green infrastructure deployment to be used for climate change adaptation and mitigation can be used by urban planners and researchers to assess future flood risks, catchment management protocols, catchment operations and water quality projections.

This study further developed a hydrological model depicting green roof runoff reduction abilities under two climate change scenarios, RCP4.5 and RCP8.5 and assessed the urbanization trends in Dublin to lay out the synergies between urbanization trends and changing climate. The analysis of runoff reduction in both scenarios is significant considering the rainfall events in both scenarios are more frequent and have higher intensities compared to historical conditions. The results are consistent with real life observation of runoff reduction in green roof in similar regions where high intensity rainfall leads to decreasing runoff reduction performance as well as higher frequency rainfall. It is also observed from the model that crop coefficient, representing plant evapotranspiration, highly effects runoff reduction as it is one of the most highly sensitive parameters in green roof water capture (Schmitter et al., 2016).

On the other hand, the land use change analysis showed there is a slow but increasing trend of urbanization and urban sprawl between 2006 and 2018 which corresponds to urban imperviousness. The increase in the urban green areas isn’t enough to compensate the increased urban areas in addition to the loss of agricultural and semi-natural areas. The total roof area in the city (48.25 km^2) could allow green roof retrofits to enhance the overall capacity of Dublin to tackle stormwater management more sustainably.

The modelling tool allows to incorporate hydrological simulation approach with climate change projections and land use information. It allows to assess different green roof design configurations, deployment scenarios and synergies between different green infrastructure elements which can help with urban climate change mitigation and adaptation goals.

The model in this research is based on an unpublished work conducted by Dr. Bidroha Basu (Assistant Lecturer, Munster Technological University, Cork; Adjunct Assistant Professor,

Trinity College Dublin; Research Fellow and Teaching Fellow, University College Dublin) who developed, calibrated and validated the model according to a real life green roof site data as previously mentioned. Dr. Basu's study remains unpublished due to COVID-19 related delays and setbacks.

Furthermore, this study intended to use collected data from the green roof site to provide a real life runoff reduction performance for the period between 29th February 2021 and 29th June 2021 but due to COVID-19 restrictions in Dublin, site operations and data gathering weren't possible. This is also why, bias correction could be done using runoff results taken from the original model developed by Dr. Basu, not with the actual runoff data collected from the green roof site.

It should be also noted that climate change projections are only projections and not reality. Even though the research in this field is rapidly developing, the data are subject to biases. Several bias correction methods are developing and being improved such as the method used in this study. However, hydrological models still provide invaluable resources to understand the effects future urban development features on the climate change mitigation and adaptation approaches. Using multi climate model ensembles and multi-step calibration and validation methods in hydrological model development to tackle uncertainties coming from the climate change projection data are becoming more popular among researchers (Krysanova et al., 2017; Orth et al., 2015; Huang et al., 2020). So these more complex modelling approaches and calculations may reduce the uncertainty concerning the model in this study as well.

The study is focused on using hydrological modelling tools to assess impact of green roofs on stormwater management in climate change scenarios. This approach can be used by researchers as well as planners and practitioners to mitigate flooding risk with green infrastructures. The model in this study in addition to other models developed by researchers provide relatively straight-forward methods to assess the future urban conditions in terms of stormwater infrastructure (Carter et al., 2007; Versini et al., 2015; Zahmathkesh et al., 2014; Damodaram et al., 2010; Qin et al., 2013). In addition, the impact of urban flooding and urban flooding mapping can be studied with the help of these type of hydrological models (Pathak et al., 2020; Zhao et al., 2019; Siswanto et al., 2019).

The study presented in this thesis focuses on a single green roof located at the CHQ building in Dublin. Though it is proven the green roof can reduce the runoff from 26%-55% depending on the amount of rainfall received, it should be emphasized that a single green roof cannot control flooding at a city scale. For this purpose, multiple green roofs as well as other sustainable drainage systems need to be deployed across the city in a real-world scenario and their cascading impact has the potential to control flooding at larger scale. Future research that focuses on development of hypothetical simulation models would be helpful to investigate the effectiveness of multiple green roofs in flood control in Dublin. In order to estimate the impacts that green infrastructures can have at an urban scale, several types of green infrastructures like bioswales, retention ponds, vegetative infiltration basins in addition to green roofs can be modelled in a street/neighbourhood/city scale. These larger scale models require extensive modifications in the model used in this study in order to operate and accurately assess hydrological performance (Schmitter et al., 2016). The time frame for this study didn’t allow such scope but this type of research is highly recommended.

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