

**STUDY ON THE IMPORTANCE OF GREEN BUILDINGS  
FOCUSSING ON STORMWATER MANAGEMENT USING A  
WATER BALANCE CALCULATION MODEL**

**Master Thesis**

**at Hof University**

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## **EXECUTIVE SUMMARY**

Maintaining balance in the hydrological cycle is crucial for nature, but extreme weather events such as droughts and heavy downpours can disrupt it. Unfortunately, the frequency of such events has increased in recent years and is expected to continue in the future (IPCC, 2021). Urban areas are particularly vulnerable to this condition, due to its sealed surfaces and limited green spaces resulting from anthropogenic activities. Decentralized stormwater management strategies are realised to be better in mitigating the effects of such events, and this research aims to explore the importance of green buildings in managing stormwater in the selected catchment areas. Two properties have been chosen for the study: an elementary school in Schauenstein and Hof University of Applied Science. The study examines in detail the general characteristics of the chosen areas, their historical climatic data, and the KOSTRA DATA (refer 3.7). The research analyses the selected buildings and their surrounding properties, the various components of their water balance involved, the methods to calculate them, its advantages, limitations, and requirements were also compared. Based on the study, an excel-based calculation model has been developed focusing on the stormwater management aspect, to find out the major components involved in the water balance of the green building and its surrounding properties that can control surface runoff from the property. The developed calculation model works on the major aspects of water accumulation and consumption of selected green buildings and its surroundings. The tool can be used to predict runoff from the properties during different storm events, based on which the volume of a stormwater collection tank can be calculated, which can store runoff from the catchment area and can be used during droughts for irrigation purposes, thereby reducing the pressure on drainage flow and water treatment plants. The study also tries to identify the effects of water balance parameters like rainfall, evapotranspiration and storage on runoff from a property. The model also checks the tank's condition for future storm events with a 3, 5, 10 and 100-year return period, using KOSTRA DATA 2020. Both the study areas are assumed to have green roofs, and the runoff results from the roofs occupied by them are validated using detention modeller software developed by green roof diagnostics.

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## List of Abbreviations

UHI	Urban Heat Island
DWD	Deutscher Wetter Dienst,
PET	Potential Evapotranspiration
AET	Actual Evapotranspiration
ET	Evapotranspiration
R	Runoff
P	Precipitation
CSO	Combined Sewer Overflow
IPCC	The Intergovernmental Panel on Climate Change
GPM	Gallons Per Minute
PSI	Pound-force per square inch
WHC	Water Holding Capacity
PWP	Permanent Wilting Point
CDC	Climate Data Centre
SCS-CN	Soil Conservation Service- curve number
GI	Green Infrastructure

# **1. Introduction**

## **1.1. General**

Climate change is usually described as change in average temperature or precipitation, whereas most of socio-economic costs related to climate change happens from change in the frequency or severity of extreme events. Grave weather events are growing more frequent worldwide, causing serious problems for both society and ecosystems. The frequency and severity of extreme weather events like heatwaves, torrential rain, and droughts have grown over the past few decades, and these trends are projected to continue in the future, according to the Intergovernmental Panel on Climate Change (IPCC, 2021). In total, the extreme events over the past few decades shows a more frequent trend than before. Some areas have faced severe drought while other areas face heavy precipitation and in some areas, both extremes occur in a frequent manner. Few regions also face rainfall with heavy intense burst, which can eventually lead to flash floods. Over the last 50 years, the amount of rainfall has raised by 7% globally, most of it has happened due to rise in frequency of heavy downpours (Huber & Gullede, 2011).

In the meantime, the heat waves have also become more humid, resulting an increase in biological heat stress, gradually results in increase in night-time temperature which also resulted in heat related deaths (Huber & Gullede, 2011). Recent studies ( Fernandez Milan & Creutzig, 2015; Sanderson & McCarthy, 2011; Bank, 2020) also show that a several fold increase in occurrence, severity and duration of global heat waves will happen in future regardless of emission scenarios. Hence the heat stress in urban areas will be higher than the combined effects of Urban heat island (UHI) effect and heat wave effect. The residents in urban areas are facing not only rise in global temperature but also in local temperature due to UHI effect. UHI effect causes direct and indirect effects on human health. Direct impacts vary from fatigue and discomfort, heart attacks and even death. Whereas indirect impacts include rise in accident cases, forest fire risks, water unavailability, agricultural damages etc (Bank, 2020).

Here comes the importance of stormwater management strategies using green buildings in urban areas. The heavy overflow or run off can be reduced or delayed and hence effects like soil loss and Combined Sewer Overflow (CSO) can be reduced to a large extend. Also, if the excess stormwater is stored wisely, it can also be used in dry seasons and can reduce the

effects of droughts in urban cities. Some of the best management strategies used in green buildings for water management include rainwater harvesting tank, green roofs, rain gardens, greywater recycling unit, pressure reduction valve installations, dual flush toilets etc (How to Increase Water Efficiency in Green Buildings?).

Even though green buildings help in overall water management of the building, this study focuses only on the stormwater management aspects of green buildings. Usually under the influence of gravity, rainwater flows and joins water bodies like rivers or sea. But due to urbanisation, a large area of natural land got converted into impervious land and hence infiltration and drainage are affected. Hence the runoff of storm water is increasing year after year. Green buildings and their stormwater management techniques are focusing on holding this stormwater within the building and using it for different purposes, thereby reducing the pressure on drainage flow and water treatment plants (How to Increase Water Efficiency in Green Buildings?).

## **1.2. Problem statement and motivation**

Many urban areas are exposed to coastal, pluvial and in recent times to surface and flash flooding. With their large river catchments, many countries are experiencing heavy losses due to riverine flooding for the past few years. Moreover, localised urban floods are also a matter of concern in recent period. The flood events happened in Germany in the years 2002, 2013 and 2021, which resulted in heavy economic losses are some of the examples. Predictions depicts that intense rainfall and drought are found to be more expected in future while precipitation trends vary seasonally and regionally (Surminski, Roezer, & Golnaraghi, 2020).

Given the urgency of the situation, there is a need to develop strategies to mitigate their impacts and adapt to their effects. This thesis aims to investigate the trends and patterns of weather events in the selected catchment areas (refer sections 2.1 and 2.2). Even though a holistic water management strategy is needed to lessen the impact of extreme events, the study focuses only on one of its important parts, the green buildings, its significance on stormwater management and how successfully its components can be applied at the chosen study regions. Also, after studying different methods to find out the water balance components of the green buildings and its surrounding premises, a comparative study has also been made to identify the advantages, limitations and requirements of each method. On the basis of these study results, an excel calculation model has been created that

incorporates the major elements of the water balance of green buildings that can control runoff from the property, and it aids in determining runoff from the property during severe weather events.

The findings of this thesis will contribute to the understanding of how well different components of green buildings can be incorporated in a building/property and how well stormwater runoff can be saved and can be used at the time of drought within the property itself, by which a proper balance of water can be achieved between drought and precipitation events. The term balance is used to explain the condition in which there is no excess flow from the property at the time of normal- heavy precipitation events and since the stored water can be used at the time of drought, no external water sources are needed as well. The external inflow and outflow into/ from the property is minimised to an extent, keeping a balance between the water accumulation and consumption volume with the use of green building components. The study also focuses on the importance of rainwater harvesting tanks and the concept of purple-green roofs, factors affecting its performance and to understand how its retention-detention properties helps in stormwater management in cities.

### **1.3. Objectives**

The specific objective of the study includes:

- Understanding the importance of green buildings and their components in stormwater management.
- Literature research on the different components involved in the water balance of a green building and its surrounding properties, factors affecting them, various methods to find them out and to identify its requirements, advantages, and limitations.
- To develop a calculation model in excel, focusing on stormwater management aspect of green buildings. It helps to find out the various components involved in the water balance of the green building and its surrounding premises that can control the runoff from the property, using the major aspects of water accumulation and consumption of the green building.

## 1.4. Structure of thesis

The thesis including the introductory chapter is divided into seven chapters. An overview of the chapters is given below:

**Chapter 2:** includes general data about the chosen study area, its climatic data pattern and KOSTRA DATA 2020. It also includes the justification for choosing the particular study areas.

**Chapter 3:** includes the results of literature study on water balance of green buildings and its surroundings using the major aspects of water accumulation and consumption of the green building, its major components involved, factors affecting them, different green buildings components and their importance in stormwater management.

**Chapter 4:** summarises different methods to calculate the major water balance components of green buildings and its surroundings like runoff, storage (retention and detention) and evapotranspiration that can control surface runoff from the property.

**Chapter 5:** contains the details of the calculation model developed in excel focusing on stormwater management aspect of green buildings, to find out the various components involved in the water balance of the green building and its nearby premises that can control surface runoff from the property, using the major aspects of water accumulation and consumption of the building.

**Chapter 6:** includes the results of the calculation model for the two study areas. It also includes a comparative study of different methods to find out the runoff, storage and evapotranspiration of a catchment area. The study results involve the advantages, limitations and requirements involved in each method.

**Chapter 7:** includes conclusion of the whole study, limits of the study, suggestion of three recommendations which can be used as a guideline for future study and also future scope of the work.

## 2. Study area and its importance

Two small-sized catchment areas have been taken for the study. They include the elementary school at Schauenstein city and the Hof university of applied science in Bayern.

### 2.1. Schauenstein Elementary school

#### 2.1.1. General

In Germany's Bavarian region, Schauenstein is a small city with a 26.66 km<sup>2</sup> land area. It is a municipality located in Upper Franconia's Hof district, which is also the district's administrative district, making it a part of the Upper Franconia region. The position of Schauenstein city in Franconia region in Bavaria is shown in Figure 1 below. The city's highest point is about 638 meters above sea level. The city is highly known for its beautiful architecture and extensive history. The city has about 2000 inhabitants. It is located at a latitude of 50°16'N and longitude of 11°46' E (The Schauenstein City, 2023).

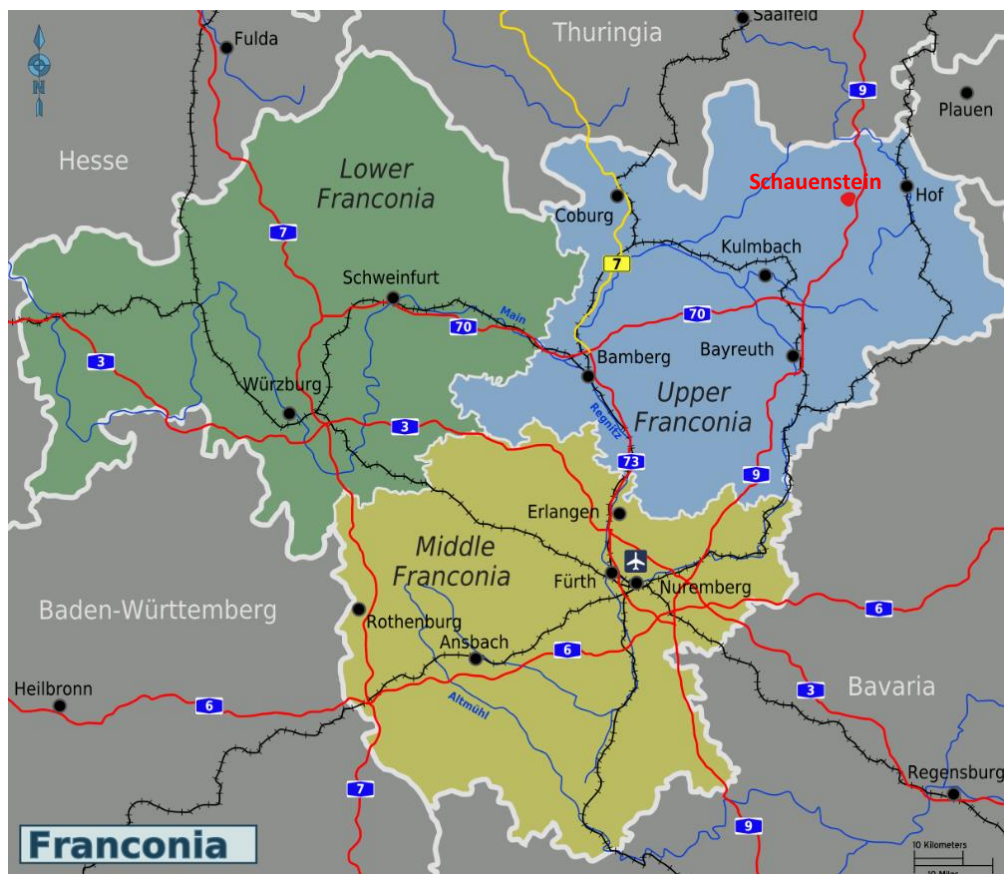


Figure 1 :Location of Schauenstein in Franconia region (Franconia, 2023).

Elementary School in Schauenstein are attended by students from Schauenstein, Leupolsgrün and other nearby districts. It has an average area of about 3,300 m<sup>2</sup> with three

major buildings. The Figure 2 below shows the image of the elementary school building in Schauenstein, which is the first catchment area taken for the study.



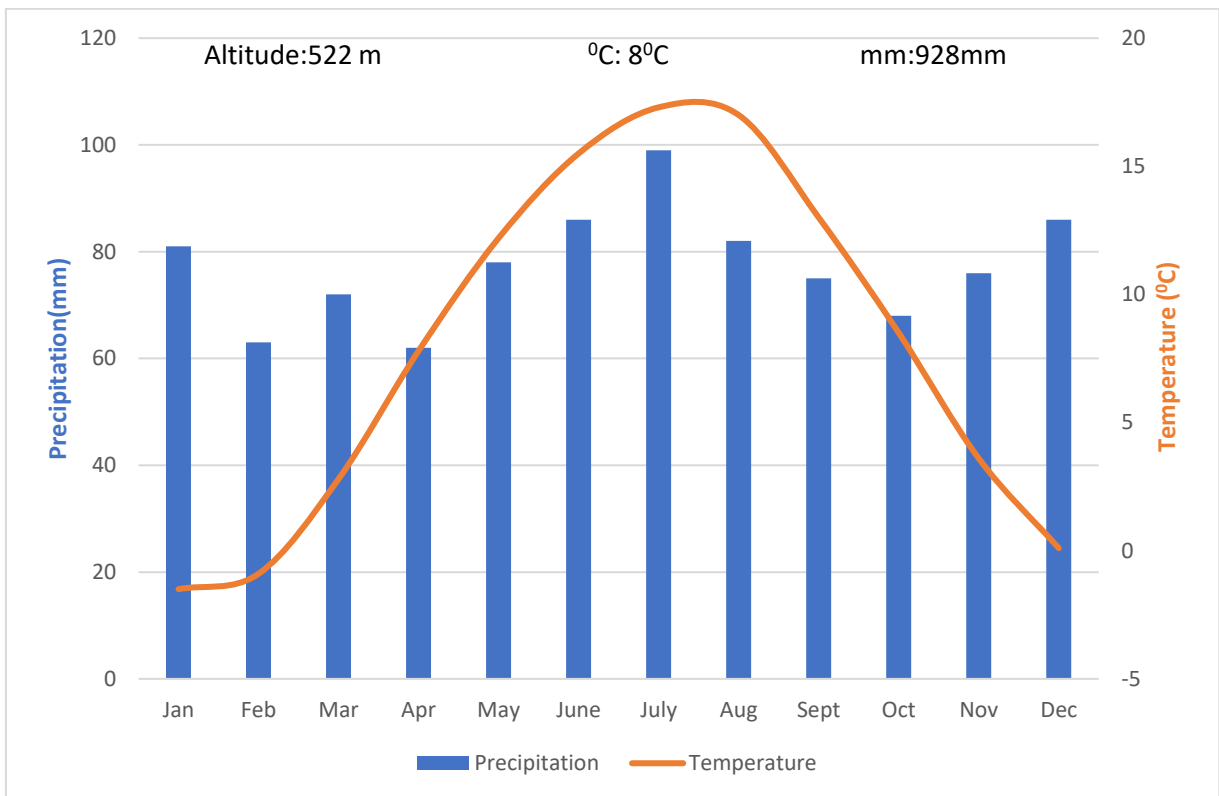
*Figure 2: Schauenstein Elementary School (The Schauenstein City, 2023)*

Renovations works are currently being implemented in the school buildings. For improving the stormwater management strategies of the school building, a purple roof has been suggested for one of the buildings of the school. For making better use of the storm water collected, a rainwater harvesting tank is also suggested, which has the ability to collect and store stormwater runoff from the purple green roof and from the sealed surface of the property. The water harvesting tank is suggested to be used for retaining the excess water at the time of heavy rainfall and to be used during dry weather conditions for watering the green roof and the green space areas in front of the school.

### **2.1.2. Climatic data**

City of Schauenstein is classified to have warm and moderate temperature. It has a significant precipitation throughout the year. Even for the driest season, Schauenstein experiences a lot of rainfall. Köppen and Geiger climate classification system is one of the most widely used climate classification system in the world. It has divided the world into five different climatic zones (zones A, B, C, D, E) based on its temperature, precipitation and vegetation grown. Each zone has been subdivided based on its coldness of summer and warmth of the winter (Köppen climate classification system, 2021). According to Köppen

and Geiger climate classification, Schauenstein belongs to Zone C (warm mild temperature) subdivided into Cfb (without dry season and warm summer, temperate oceanic climate classification (Climate in Schauenstein, 2023)). The average annual temperature of Schauenstein is around 8°C and the average precipitation is around 928 mm per year. Summer days in Schauenstein starts by the end of June and ends in September. Regarding precipitation, April is the month to experience minimum rainfall with an average of 62 mm. On the other hand, the month of July experiences maximum rainfall of around 99mm. The highest temperature is observed in the month of July with an average value of 17.3°C, whereas January is the coldest month with an average temperature of -1.5°C. The Figure 3 below depicts a graph showing the average temperature and precipitation for the city of Schauenstein from the month of January to December (Climate in Schauenstein, 2023).



*Figure 3: Graph showing average temperature and precipitation of Schauenstein (designed referring to (Climate Schauenstein, 2023))*

Throughout the year, precipitation varies by 37 mm between the driest and wettest periods. Also, temperature shows a variation of about 18.8°C. November has the highest relative humidity of about 88% and April with the least value 69.18%. December is observed to be the wettest month for about 15.57 days and September to be the driest month of 11.57 days.



Table1 below shows the average, minimum, maximum temperature, precipitation, humidity and number of rainy days for each month from 1991-2021

Table 1: Climatic data from the years 1991-2021 for city of Schauenstein (*Climate Schauenstein, 2023*)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Average Temp (°C)	-1.5	-0.9	2.8	7.8	12.2	15.5	17.3	17	13	8.5	3.6	0.1
Minimum Temp (°C)	-3.9	-4	-0.9	3.2	7.7	11	12.9	12.8	9.2	5.5	1.5	-1.8
Maximum Temp (°C)	0.9	2.3	6.7	12.3	16.4	19.6	21.4	21.2	16.8	11.8	6	2.1
Precipitation (mm)	81	63	72	62	78	86	99	82	75	68	76	86
Humidity (%)	86	84	78	69	70	70	69	70	76	83	88	87
Rainy days	11	9	10	9	10	10	11	10	9	9	10	12
Average sun hours	2.3	3.5	4.9	7.7	8.7	9.8	10	9.2	6.3	4.2	2.6	2.1

Considering the snowfall, the city of Schauenstein experiences a seasonal change in monthly snowfall. The month of snow extends for 5.1 months from the months of November till April with an average fall of at least 1 inch. January experiences the highest snowfall of about 4.1 inches. The snowless months are from April to November with an average of 0 inches. The temperature and precipitation estimations of Schauenstein are made from 3 nearby weather stations. They are Hof- Plauen Airport, Grafenwoehr and Erfurt- Weimar Airport. The value of Schauenstein is taken by taking the weighted average of individual values for above three stations, with weights proportional to the distance between Schauenstein and the individual station (Climate in Schauenstein, 2023).

### 2.1.3. KOSTRA DATA 2020

The grid position 156169 includes the Schauenstein region. The KOSTRA-DWD 2020 (refer section 3.7) for the region of Schauenstein is depicted in the Figure 4 below (Deutscher Wetter Dienst, KOSTRA-DWD, 2023).

Regenspende und Bemessungsniederschlagswerte in Abhängigkeit von Wiederkehrzeit T und Dauerstufe D

Dauerstufe D	Wiederkehrzeit T																		
	1 a		2 a		3 a		5 a		10 a		20 a		30 a		50 a		100 a		
	min	Std	mm	l / (s ha)	mm	l / (s ha)	mm	l / (s ha)	mm	l / (s ha)	mm	l / (s ha)	mm	l / (s ha)	mm	l / (s ha)	mm	l / (s ha)	
5		6,8	226,7	8,4	280,0	9,3	310,0	10,6	353,3	12,5	416,7	14,4	480,0	15,6	520,0	17,3	576,7	19,6	653,3
10		9,1	151,7	11,2	186,7	12,5	208,3	14,2	236,7	16,7	278,3	19,3	321,7	20,9	348,3	23,1	385,0	26,3	438,3
15		10,5	116,7	13,0	144,4	14,5	161,1	16,5	183,3	19,4	215,6	22,3	247,8	24,3	270,0	26,8	297,8	30,4	337,8
20		11,6	96,7	14,3	119,2	16,0	133,3	18,1	150,8	21,3	177,5	24,6	205,0	26,7	222,5	29,5	245,8	33,5	279,2
30		13,2	73,3	16,2	90,0	18,1	100,6	20,6	114,4	24,2	134,4	27,9	155,0	30,3	168,3	33,5	186,1	38,1	211,7
45		14,8	54,8	18,3	67,8	20,4	75,6	23,2	85,9	27,3	101,1	31,5	116,7	34,2	126,7	37,8	140,0	42,9	158,9
60	1	16,1	44,7	19,9	55,3	22,2	61,7	25,2	70,0	29,6	82,2	34,2	95,0	37,1	103,1	41,0	113,9	46,6	129,4
90	1,5	18,0	33,3	22,2	41,1	24,8	45,9	28,2	52,2	33,2	61,5	38,2	70,7	41,6	77,0	45,9	85,0	52,2	96,7
120	2	19,5	27,1	24,0	33,3	26,9	37,4	30,6	42,5	35,9	49,9	41,4	57,5	45,0	62,5	49,7	69,0	56,4	78,3
180	3	21,7	20,1	26,8	24,8	29,9	27,7	34,1	31,6	40,0	37,0	46,1	42,7	50,1	46,4	55,4	51,3	62,9	58,2
240	4	23,5	16,3	28,9	20,1	32,3	22,4	36,8	25,6	43,2	30,0	49,8	34,6	54,1	37,6	59,8	41,5	67,9	47,2
360	6	26,1	12,1	32,2	14,9	36,0	16,7	40,9	18,9	48,0	22,2	55,4	25,6	60,2	27,9	66,5	30,8	75,6	35,0
540	9	29,0	9,0	35,8	11,0	40,0	12,3	45,5	14,0	53,4	16,5	61,6	19,0	67,0	20,7	74,0	22,8	84,0	25,9
720	12	31,3	7,2	38,6	8,9	43,1	10,0	49,1	11,4	57,6	13,3	66,4	15,4	72,2	16,7	79,7	18,4	90,6	21,0
1080	18	34,8	5,4	42,9	6,6	47,9	7,4	54,5	8,4	64,0	9,9	73,8	11,4	80,2	12,4	88,6	13,7	100,7	15,5
1440	24	37,5	4,3	46,2	5,3	51,6	6,0	58,7	6,8	69,0	8,0	79,5	9,2	86,4	10,0	95,5	11,1	108,5	12,6
2880	48	44,9	2,6	55,3	3,2	61,8	3,6	70,3	4,1	82,6	4,8	95,2	5,5	103,5	6,0	114,3	6,6	129,8	7,5
4320	72	49,9	1,9	61,5	2,4	68,7	2,7	78,1	3,0	91,7	3,5	105,7	4,1	114,9	4,4	127,0	4,9	144,2	5,6
5760	96	53,7	1,6	66,2	1,9	74,0	2,1	84,1	2,4	98,8	2,9	113,9	3,3	123,8	3,6	136,8	4,0	155,4	4,5
7200	120	56,9	1,3	70,2	1,6	78,4	1,8	89,2	2,1	104,7	2,4	120,7	2,8	131,2	3,0	144,9	3,4	164,6	3,8
8640	144	59,7	1,2	73,6	1,4	82,2	1,6	93,5	1,8	109,7	2,1	126,5	2,4	137,5	2,7	151,9	2,9	172,6	3,3
10080	168	62,1	1,0	76,6	1,3	85,5	1,4	97,3	1,6	114,2	1,9	131,7	2,2	143,1	2,4	158,1	2,6	179,6	3,0

Figure 4: KOSTRA DWD 2020 DATA for Schauenstein (Deutscher Wetter Dienst, KOSTRA-DWD, 2023)

#### 2.1.4. Justification for the chosen study area

The recognition of the disproportionate impact of climate change on rural areas has led to an increasing importance placed on regional adaptation measures. In response to this need, the Hof University of Applied Science research institute, inwa, has initiated a research project called Smart Sponge Region (SPORE), with a particular focus on the regions of Hof, Hoch franken, and Upper Franconia. The project aims to preserve ecological function, promote sustainable use of natural resources, and maintain a balance between heavy rainfall and dry periods (SPORE - Smart Sponge Region, 2023).

Unfortunately, the adoption of digital solutions in water management has been hindered by various obstacles such as limited resources (including finances, time, and expertise), employee resistance to change, and insufficient IT infrastructure. Pilot projects might be implemented to provide real-world examples and promote learning through practice to get over these challenges. Choosing a subtask to represent the entire project, also known as the "anyway strategy," enables the transfer of knowledge and experiences to other subtasks and the overall project. Better choices can be made for the project's later phases based on the information and limits discovered in the subtask (Müller-Czygan, 2021).

In line with the anyway strategy, the inwa research institute has selected the city of Schauenstein as the pilot project for the Smart Sponge Region (SPORE) project, thus making it the first study area for the research. As an initial step towards achieving the goals of the SPORE project, a study was conducted on a small catchment area within Schauenstein - the

elementary school in the city. The experiences, analyses, and findings derived from this subtask will be utilized in the broader SPORE project.

## 2.2. Hochschule Hof

### 2.2.1. General

The Hochschule Hof, a Bavarian university founded in 1994, has been chosen as the second study area. The city of Hof is located at a latitude of 50°31' N and longitude of 11°87' E. The campus mainly consists of four main buildings A, B, C, D, the canteen building E, building G (iisys), Einstein Lab building and the mobile units between buildings A and B. The total area of all the buildings is approximately 15300m<sup>2</sup>. The google image of the Hochschule campus which is the second catchment area taken for study is shown in Figure 5 below.

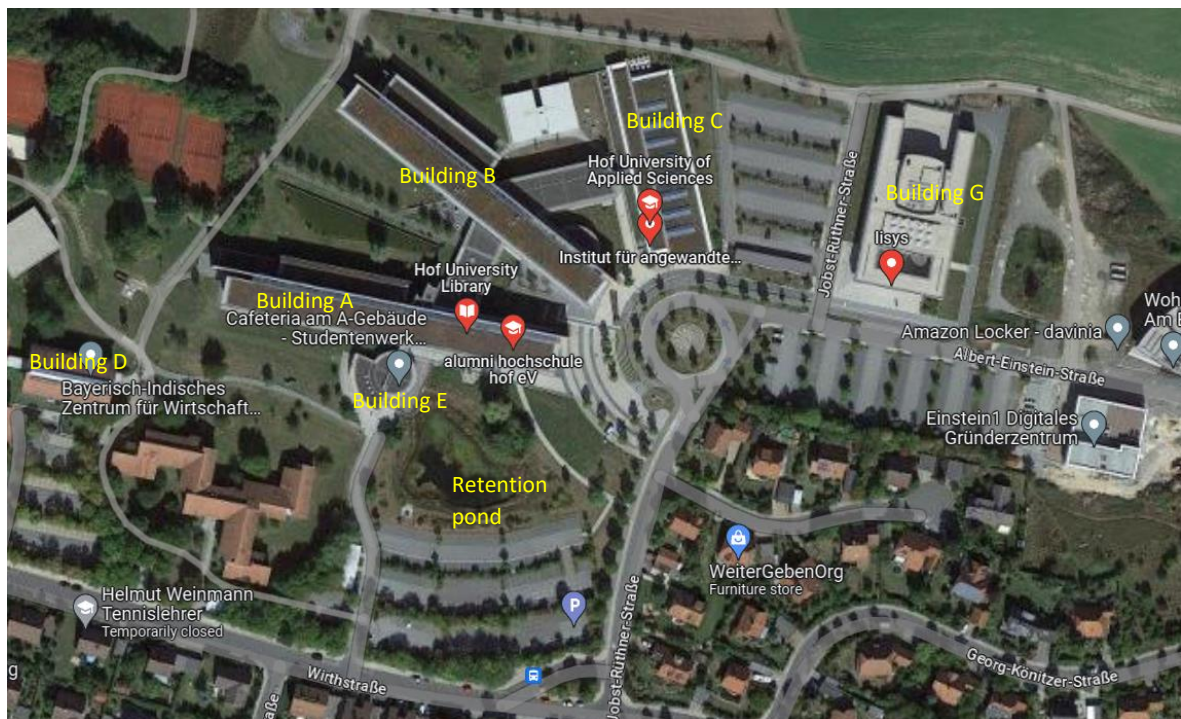


Figure 5: Plan view of Hochschule Hof (taken from google map)

To understand the significance of the green buildings in stormwater management, a study was conducted using the developed calculation model, to determine the runoff from the campus with and without purple roofs. To make better use of the runoff stormwater, the study also considered the importance of the retention pond located at the front of the campus area. The capacity of the pond was assessed to know, if it could collect and store rainwater run-off from all the purple roofs, thereby reducing the pressure on drainage and treatment plants. It was also checked whether the water collected in the pond is sufficient enough to irrigate the green roofs during dry weather conditions.

## 2.2.2. Climatic data

Due to its proximity to Schauenstein, Hof City has weather conditions that are nearly identical to those of Schauenstein. Additionally, Hof's climate is mild, warm, and has a lot of annual precipitation. Hof also falls under the Cfb classification of the Köppen and Geiger climate classification system. In Hof, the yearly average temperature is around 8.1°C and 886 mm of precipitation occurs yearly. June marks the start of summer and concludes in September (Climate data, 2021). The warmest month is July with an average temperature of 17.4°C. The lowest monthly average temperature of the year is -1.3°C in January. The driest month on average is February and there is a 40 mm difference from July, which is the wettest month (Climate data, 2021).

## 2.2.3. KOSTRA DATA 2020

The grid position 154171 includes the Hof region. The KOSTRA-DWD 2020 for the Hof region is shown below in Figure 6 (Deutscher Wetter Dienst, KOSTRA-DWD, 2023).

**Rasterfeld 154171**  
(Zeile 154, Spalte 171)

**Regenspende und Bemessungsniederschlagswerte in Abhängigkeit von Wiederkehrzeit T und Dauerstufe D**

Dauerstufe D	Wiederkehrzeit T																		
	1 a	2 a	3 a	5 a	10 a	20 a	30 a	50 a	100 a	1 a	2 a	3 a	5 a	10 a	20 a	30 a	50 a	100 a	
min	Std	mm	l / (s ha)	mm	l / (s ha)	mm	l / (s ha)	mm	l / (s ha)	mm	l / (s ha)	mm	l / (s ha)	mm	l / (s ha)	mm	l / (s ha)	mm	l / (s ha)
5		6,7	223,3	8,3	276,7	9,2	306,7	10,5	350,0	12,4	413,3	14,3	476,7	15,5	516,7	17,2	573,3	19,5	650,0
10		9,0	150,0	11,1	185,0	12,5	208,3	14,2	236,7	16,7	278,3	19,3	321,7	20,9	348,3	23,2	386,7	26,3	438,3
15		10,4	115,6	12,9	143,3	14,4	160,0	16,4	182,2	19,3	214,4	22,3	247,8	24,3	270,0	26,8	297,8	30,5	338,9
20		11,5	95,8	14,2	118,3	15,9	132,5	18,1	150,8	21,3	177,5	24,5	204,2	26,7	222,5	29,5	245,8	33,5	279,2
30		13,0	72,2	16,1	89,4	18,0	100,0	20,5	113,9	24,1	133,9	27,8	154,4	30,2	167,8	33,4	185,6	38,0	211,1
45		14,6	54,1	18,1	67,0	20,2	74,8	23,0	85,2	27,0	100,0	31,2	115,6	33,9	125,6	37,5	138,9	42,7	158,1
60	1	15,8	43,9	19,5	54,2	21,9	60,8	24,9	69,2	29,3	81,4	33,8	93,9	36,7	101,9	40,6	112,8	46,1	128,1
90	1,5	17,6	32,6	21,8	40,4	24,3	45,0	27,7	51,3	32,6	60,4	37,6	69,6	40,9	75,7	45,2	83,7	51,4	95,2
120	2	19,0	26,4	23,4	32,5	26,2	36,4	29,8	41,4	35,1	48,8	40,5	56,3	44,0	61,1	48,7	67,6	55,3	76,8
180	3	21,0	19,4	26,0	24,1	29,0	26,9	33,1	30,6	38,9	36,0	44,9	41,6	48,8	45,2	53,9	49,9	61,3	56,8
240	4	22,6	15,7	27,9	19,4	31,2	21,7	35,5	24,7	41,8	29,0	48,2	33,5	52,4	36,4	57,9	40,2	65,9	45,8
360	6	24,9	11,5	30,8	14,3	34,5	16,0	39,3	18,2	46,2	21,4	53,3	24,7	57,9	26,8	64,0	29,6	72,8	33,7
540	9	27,5	8,5	34,0	10,5	38,1	11,8	43,4	13,4	51,0	15,7	58,8	18,1	64,0	19,8	70,7	21,8	80,4	24,8
720	12	29,5	6,8	36,5	8,4	40,8	9,4	46,5	10,8	54,7	12,7	63,1	14,6	68,6	15,9	75,9	17,6	86,2	20,0
1080	18	32,6	5,0	40,3	6,2	45,1	7,0	51,3	7,9	60,3	9,3	69,7	10,8	75,7	11,7	83,7	12,9	95,2	14,7
1440	24	35,0	4,1	43,2	5,0	48,3	5,6	55,0	6,4	64,7	7,5	74,7	8,6	81,2	9,4	89,8	10,4	102,0	11,8
2880	48	41,3	2,4	51,1	3,0	57,1	3,3	65,1	3,8	76,5	4,4	88,3	5,1	96,0	5,6	106,2	6,1	120,7	7,0
4320	72	45,6	1,8	56,4	2,2	63,0	2,4	71,8	2,8	84,4	3,3	97,4	3,8	105,9	4,1	117,1	4,5	133,1	5,1
5760	96	48,9	1,4	60,4	1,7	67,5	2,0	76,9	2,2	90,5	2,6	104,4	3,0	113,5	3,3	125,5	3,6	142,6	4,1
7200	120	51,6	1,2	63,7	1,5	71,3	1,7	81,2	1,9	95,5	2,2	110,2	2,6	119,8	2,8	132,4	3,1	150,5	3,5
8640	144	53,9	1,0	66,6	1,3	74,5	1,4	84,8	1,6	99,7	1,9	115,1	2,2	125,2	2,4	138,4	2,7	157,3	3,0
10080	168	55,9	0,9	69,1	1,1	77,3	1,3	88,1	1,5	103,5	1,7	119,5	2,0	129,9	2,1	143,6	2,4	163,2	2,7

Figure 6: KOSTRA DWD 2020 DATA for Hof (Deutscher Wetter Dienst, KOSTRA-DWD, 2023)

## 2.2.4. Justification for the chosen study area

As a part of the SPORE project (described in section 2.1.4), a smart sponge campus at Hof University is planned to develop, which focuses on smart water management practises. The research findings presented here represent the first steps towards achieving these goals, and

as such, the study made on Hof University of applied Science represents a small but significant contribution to this broader initiative.

Secondly, the location of Hochschule compared to other areas of the Hof city is another factor in the choice being made. There is a probability of frequent heavy precipitation in future because extreme weather events have been more regular during the previous few decades. If something similar occurred in Hof, water from buildings located on high elevated areas would flow towards the city centre located at lower altitudes and may cause a significant socio-economic loss. Herein lies the importance of Hochschule's stormwater management initiatives, to reduce the overflow into the city centre.

### 3. General literature review

#### 3.1. Hydrological cycle

Hydrological cycle, also known as water cycle, is the natural and continual movement of water near or below the surface of earth, in which water either moves from one place to another or get transferred from one form to another (solid, liquid or gas). The cycle usually starts with the evaporation of water from the water bodies with the help of heat energy from the sun. Due to the effect of convection, the evaporated form from the waterbodies moves up to atmosphere and when conditions are suitable, the vapour gets converted into precipitation (in the form of rain, snow or ice) (Mohajerani, Zema, Lucas-Borja, & Casper, 2021). Precipitation can either be intercepted by vegetation or can be evaporated back into the atmosphere. This process is termed as interception. It can also be infiltrated into the soil and can be evaporated through the soil or transpired through vegetation. This process is termed as evapotranspiration. The excess precipitation can be turned into an overland water stream known as surface runoff, which could be transferred into deeper soil layers known as infiltration. Since all these processes are dealing with interaction and movement of precipitation it is termed as hydrological processes and they all vary in time and space (Mohajerani, Zema, Lucas-Borja, & Casper, 2021). Figure 7 below shows the different components of a hydrological cycle explained above.

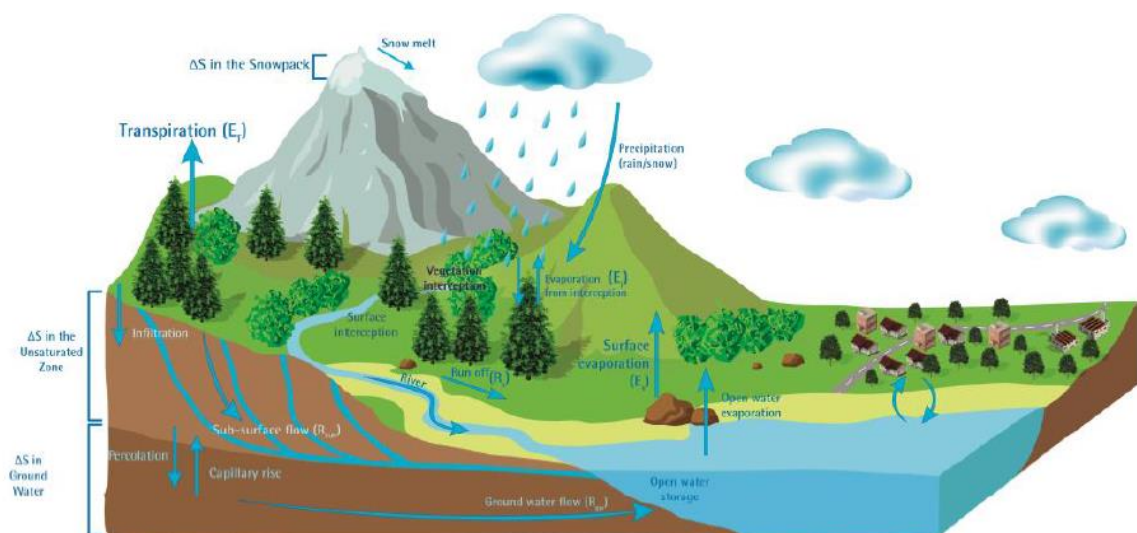


Figure 7: Key components of hydrological cycle (European Commission, 2015)

### **3.2. Water balance**

According to the law of conservation of mass, the rate of change of storage within the hydro system over a specific period should be equal to difference between the rate of inflow and outflow of water through the boundaries. To explain the flow of water into and out of the system and to estimate the amount of water stored in various hydro systems, a water balance equation is needed. The spatial scale of the water balance equation ranges from a small sample of soil (plot scale) to entire catchment or global scale. To find the water balance, it is essential to first find out the boundaries of the hydro system which is considered as control volume. It can be small as a soil sample or big as a catchment area, within which the fluxes of water, energy and mass which are either stored internally or transported across the boundaries (Mohajerani, Zema, Lucas-Borja, & Casper, 2021).

Developing water balance helps to analyse the main components of natural hydrological cycle (without human interventions) as well as significant input and output components due to human influence (abstraction, returns etc.) into a single framework. Studies shows that, if the meteorological conditions, various hydrological processes, vegetation are studied carefully, simple water balance models are quite efficient in explaining various hydrological processes, calculating runoff from the catchment area and in studying the influence of human interventions in a large scale. The model helps to compare different hydrological processes like evapotranspiration, precipitation, soil storage and runoff (Sutcliffe, 2004). When the water balance is studied, the climatic and physical parameters of the basin are known beforehand, information regarding current and future water volumes and additional understanding of the complex process of basin runoff are provided.

Studies review approaches for defining water balance and its essential elements, analysing numerical models for calculating water balance, providing examples of model implementations (Ivezic, Bekic, & Zugaj, 2017). The consequences of land use change on water balance and estimating runoff in understudied watersheds are ongoing issues of scientific and expert ecohydrological studies, but the estimation of water flux between water balance components remains as an intriguing and difficult hydrological task (Zhang et al., 2008; Todini, 2007; Alemaw and Chaoka, 2003 as cited in (Ivezic, Bekic, & Zugaj, 2017)).

The prediction of a regional water balance, the evaluation of the influence of anthropogenic activities and climate changes on surface runoff, the planning and allocation of freshwater resources, in engineering applications like bridge management systems etc. are just a few of

the studies and practical issues where the calculation of water balance is used. The insight into intricate processes that take place in connection to various spatial and temporal relations can be gained by understanding water balance in relation to meteorological and physical basin aspects (Ivezic, Bekic, & Zugaj, 2017).

As already explained above, water balance modelling can be applied in any hydrological system which can be as small as a soil sample or as big as an entire catchment area (Mohajerani, Zema, Lucas-Borja, & Casper, 2021). The present research investigates the water balance of selected green buildings (Schauenstein elementary school and Hof University of applied science) using modelling techniques. The study examines various methods to determine the water balance components of green buildings and surrounding areas, comparing the advantages, limitations, and requirements of each method. Based on the findings, an Excel-based calculation model is developed, which integrates major elements of the water balance (e.g., rainfall, evapotranspiration, and storage) that can control the surface runoff from the property. The term "balance" is used to describe a condition where no excess flow occurs from the property during normal to heavy precipitation events, and stored water can be used during drought, eliminating the need for external water sources. The use of green building components helps to minimize external inflow and outflow, maintaining a balance between water accumulation and consumption.

### **3.3. Water balance components**

The major components involved in the water balance of the green building and its surrounding premises were identified and studied in detail. The components taken into consideration are precipitation, runoff, storage (retention and detention) and evapotranspiration.

#### **3.3.1. Precipitation**

Precipitation is one of the hydrological cycle components in the form of atmospheric water. Also, it contributes to the water balance of the green buildings and its surrounding properties on a major scale and contains water that drops down into the property from the atmosphere in the form of liquid or solid. The liquid form of precipitation is known as rainfall, whereas other forms include snowfall, hail or sleet. The major characteristic of rainfall includes (Ivezic, Bekic, & Zugaj, 2017):



- Depth: It is the total volume of the precipitation on an area, if it cannot be evaporated, drained, percolated form the area.
- Duration: the time period between start and end of precipitation.
- Intensity time: ratio of precipitation volume to the rainfall duration.
- Frequency: Also known as return period, shows how often a rainfall with a particular character is likely to occur

### **3.3.2. Evapotranspiration**

The hydrologic cycle of green infrastructure (GI) involves an essential component, evapotranspiration (ET), which is analysed in this study. Evaporation is the process by which water goes back into the atmosphere either from soil or from water bodies, whereas transpiration is the process by which plants let the water go through their leaves' stomata. Evapotranspiration is the process of return of water vapour back into atmosphere through both these processes, evaporation and transpiration. It mainly depends on climatic conditions and vary along with these changes (Federation, 2012). ET is a dynamic process influenced by both meteorological factors (e.g., rainfall characteristics, relative humidity, and air temperature) and GSI properties (Ebrahimian, Wadzuk, & Traver, 2019). As a critical driver for green roof buildings, ET plays a crucial role in the water balance of green buildings.

It is also very important to distinguish between potential and actual evapotranspiration. Potential Evapotranspiration (PET) is the maximum possible evapotranspiration, assuming that there is no limit for soil and plant moisture content. Whereas actual evapotranspiration (AET) is the evapotranspiration that happens in limited substrate moisture contents and differences in surface conditions, plant health, physiology, and weather conditions. A precise estimation of AET is important not only for stormwater management, but also in the study for change in climate, crop water requirement management, proper usage of water resources (Hendriks, 2010, Zhao et al., 2013 as cited in (Stefferdud, 2016)).

Potential evapotranspiration is usually used in hydrological models since it is easier to calculate while depends only on climatic factors and type of vegetation, whereas actual evapotranspiration is influenced by soil type, antecedent moisture content and vegetation type. In large catchment areas with different types of land for example mountains or cities, it is found to be difficult to find accurate ET value. Due to the shadow effects, uniform solar radiation cannot be assured. Also, the urban heat island effect in cities may even more complicate the ET estimation process (Schneider, 2011).

### **3.3.3. Runoff**

Runoff management being one of the major tasks of green buildings, runoff is the next water balance component taken into consideration. Runoff is one of the ways how a catchment area reacts to a precipitation event. During a rainfall event, the part of the atmospheric water that does not percolate or infiltrate down into the soil or evapotranspirate, that flows by gravity over the catchment area is known as surface runoff. The part of runoff formed from rainfall, that takes a flow to the stream channels directly is named as direct runoff or quick flow. The other part of runoff infiltrates down into the soil and moves in a slow pace is known as base flow or delayed flow (Mohajerani, Zema, Lucas-Borja, & Casper, 2021).

The total runoff comprises of several water flow paths (Ward, 1967 as cited in (Mohajerani, Zema, Lucas-Borja, & Casper, 2021)):

- Direct precipitation over water surface: It is the part of atmospheric water that falls directly on water bodies like lakes, streams etc.
- Overland flow: It consists of surface runoff, the faster component of quick flow.
- Interflow: This flow usually occurs in unsaturated soil zone when the horizontal conductivity of the soil is much higher than the vertical conductivity. It is also known as sub surface flow which includes the water filtering down through the soil surface and its lateral movement.
- Groundwater flow: It is the flow made by percolation of the infiltrated precipitation down into the saturated zone and its movements towards the stream channel.

The runoff related to a storm event depends on the duration and rainfall intensity. The volume and runoff rate are also dependent on the distribution of rainfall amount and intensity over the catchment area. When the runoff of green buildings is considered, it depends on the characteristics of the roof area, its size, shape, slope, orientation, topography, soil type and type of vegetation used. As the size of the roof area increases, volume of runoff also increases (Mohajerani, Zema, Lucas-Borja, & Casper, 2021).

### **3.3.4. Change in storage.**

Change in storage refers to the amount of water stored in vegetation, water bodies and unsaturated soil zone is another major hydrological component of green buildings. Both infiltration and runoff are identified as two major components of hydrological cycle. Infiltration begins when rain reaches the ground surface. Runoff begins when the rainfall

exceeds the infiltration capacity of the soil. A large amount of infiltrated water goes back to the atmosphere as evapotranspiration. Some amount will also add up in groundwater recharge. Figure 8 below shows the relation between infiltration and runoff for a constant rate rainfall event. Once water has entered the soil, the movement within the soil is termed as percolation (Fangmeier, Elliot, Workman, & Huffman, 2013).

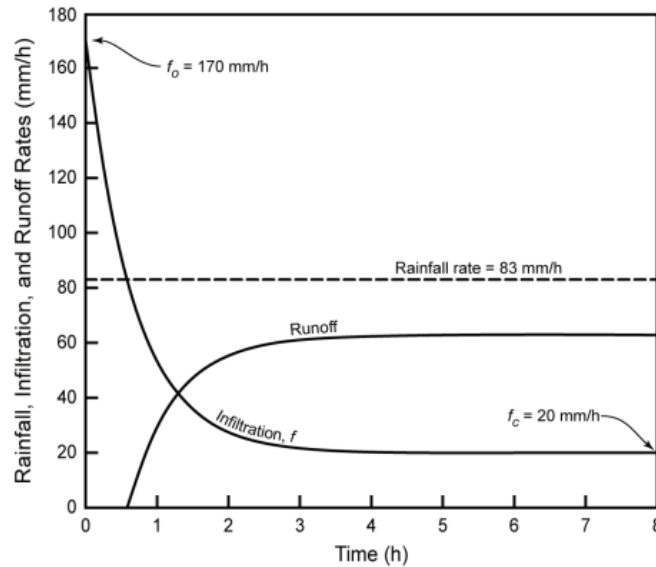


Figure 8: Relation between infiltration and runoff (Fangmeier, Elliot, Workman, & Huffman, 2013)

The infiltration into the soil depends on soil texture, degree of bonding between individual particle and arrangement of the particles. Greater the pore size, higher the infiltration rates of the stormwater. Also, the vegetation and land use cover are studied to have great influence on the infiltration capacity of the soil. Other factors influencing infiltration capacity are slope, temperature and moisture content of soil, entrapped air and soil roughness (Fangmeier, Elliot, Workman, & Huffman, 2013).

Considering green buildings retention and detention are the two major components involved in storage component. Retention is the ability of the green roof to hold back the water and later removed via evapotranspiration. Retention capacity of the green roof depends on substrate depth, type of vegetation, climatic conditions antecedent moisture conditions etc. The Figure 9 below depicts the conceptual model of substrate moisture flux in a green roof.  $WHC_{max}$  is the maximum water holding capacity of the green roof under gravity. PWP shows the minimum moisture content required by the plant below which the plants can no longer absorb water from the medium known as permanent wilting point. The difference between  $WHC_{max}$  and PWP is the  $S_{max}$  or the maximum retention capacity of the green roof which is

a clearly finite value and depends on green roof configurations. During a storm event, the soil medium of green roofs retains water upto  $WHC_{max}$  (also known as field capacity) and then runoff begins (Poe, Stovin, & Berretta, 2013).

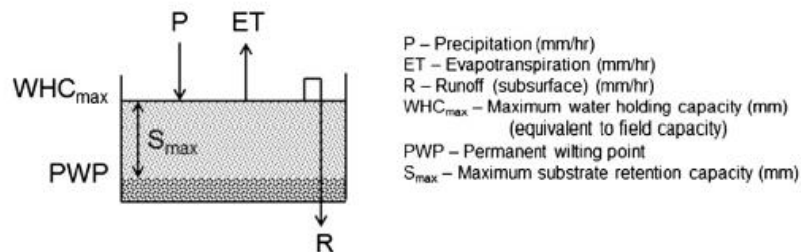


Figure 9: Conceptual model of retention capacity of a substrate in green roof (Poe, Stovin, & Berretta, 2013)

Whereas detention is the holding back of water temporarily and releasing it at a slow rate with a delay in time (Johannessen, Muthanna, & Braskerud, 2018) and reduction in peak flow. Even though the detention performance metrics like peak delay, t50 delay etc are influenced by rainfall characteristics and retention processes, the detention process in green roofs are dependent mainly on the dimensions of the green roof (slope, substrate depth, drainage layer depth) (Stovin, Vesuviano, & De-Ville, 2017).

### 3.4. Weather extremes

Many countries across the world are known for its diverse weather patterns and frequent extreme weather events in the past few years. They have a significant impact on economy, environment and social life of people. Some of the extreme weather events experienced in the past few years are heavy precipitation, flooding, droughts and heat waves (IPCC, 2021).

#### 3.4.1. Floods

Floods are described as the water overflow outside its usual boundaries. It usually happens in areas of population or in ongoing productive areas. Floods are usually classified as very localised, short-term floods, river overflows, flooding of large plains, coastal flooding, flooding due to infrastructure collapse and seasonal snowmelt flood (Camilloni, Barros, Moreiras, Poveda, & Tomasella, 2020). Precipitation is observed to be decreased in months of summer and to rise in winter with more rain and snow in hilly regions.

Two major events followed by precipitation include combined sewer overflow and soil erosion. During the time of heavy precipitation, the combined sewer system, the system

which collects water from both domestic- industrial areas along with rainwater runoff exceeds. The system hence discharges the exceeded water, in order to prevent the heavy load on wastewater treatment plant being flooded. The discharged extra water, which is untreated, flows directly into water bodies like rivers. Such a condition is termed as Storm water overflow or combined sewer overflow (CSO). For sewer system in cities, the major negative effects created by extreme precipitation events are sewer overloading and flooding in cities and heavy discharges in the form of combined sewer overflow ( Nilsen, Lier, Bjerkholt, & Lindholm, 2011). CSO contain harmful chemical and microbiological elements which are harmful for the ecosystem. The harmful substances include microbial pathogens, micropollutants, pharmaceuticals and drugs, pesticides, suspended solids, heavy metals, nutrients, microplastics et ( Botturi, et al., 2020) c. The severity of the event depends on duration of the event and quality of discharged water. The two major factors which triggers CSO is heavy rainfall events and sealed areas in urban regions. Urban areas, with reduced retention capacities will eject the whole amount of rainwater directly into sewer system which eventually results in CSO (Cools, Banfi, McNeill, Zamparutti, & Vaes, 2016).

Climate change in many regions of the world tends to increase severe rainfall events in future, with increase in runoff and decrease in infiltration rate which can also cause heavy soil loss than in the 21<sup>st</sup> century beginning. In future the rainfall erosivity tends to increase from 15.7% - 25.5% which will rise the importance of soil erosion and the importance of measures to avoid them (Panagos, et al., 2021).

### **3.4.2. Droughts**

Droughts can be defined as extreme dry period that can lasts for a long time resulting in severe deficiency in water balance which can eventually result in social, economic and environmental impacts (Wilhite, 2000 cited in (Glaser & Kahle, 2020). In the past few years, the drought events as in 2002, 2013 and 2021 in central Europe are some of the examples. The sectors like Forestry and agriculture are primarily affected due to such events with an overall damage of about 8 billion dollars. Drought also has negative impact on water balance, supply, society etc (Glaser & Kahle, 2020).

A continuous stretch of excessively dry weather that results in severe hydrological imbalances is what defines a drought (IPCC, 2012 as cited in (Camilloni, Barros, Moreiras, Poveda, & Tomasella, 2020)). The intensity, duration, and geographic reach of the incident all affect how severe the drought is. The amount of precipitation that reduces and the gravity

of the effect it has are referred to as intensity. Droughts can last for multiple years in a row, but they typically last for a minimum of two to three months (Camilloni, Barros, Moreiras, Poveda, & Tomasella, 2020).

### 3.4.3. Urban heat stress in cities

Heat waves and higher temperatures are serious issues for many urban areas in different parts of the world. Extreme temperature is one of the most hazardous events in cities. The Urban Heat Island effect is one of the common phenomena associated with characteristics of urban climate that intensifies the additional heat in urban areas at the time of heat waves that has detrimental effects on public health. The temperature difference between urban and rural areas is defined as Urban Heat Island effect (UHI) (McCarthy & Sanderson, 2011). The UHI effect is an outcome of different physical factors. Due to the high intensity of sealed land use pattern and less vegetation cover, cities are experiencing higher temperature compared to the surrounding regions. In recent years, more than 50% of the total population lives in urban areas, which lead to changes in land use pattern affecting regional climate and urban air temperatures. These effects are even intensified by anthropogenic activities like industrial, transportation activities. Limited circulation of air and reduced cooling at night results in warmer cities and makes them more prone to heat waves. Also, the building elements used in urban areas increases the absorption of solar radiation and aggravates heating inside buildings (Bank, 2020). Figure 10 below shows the schematic illustration of UHI effect that results in higher temperature in urban areas. The heat load is lesser in rural areas than in sealed urban areas.

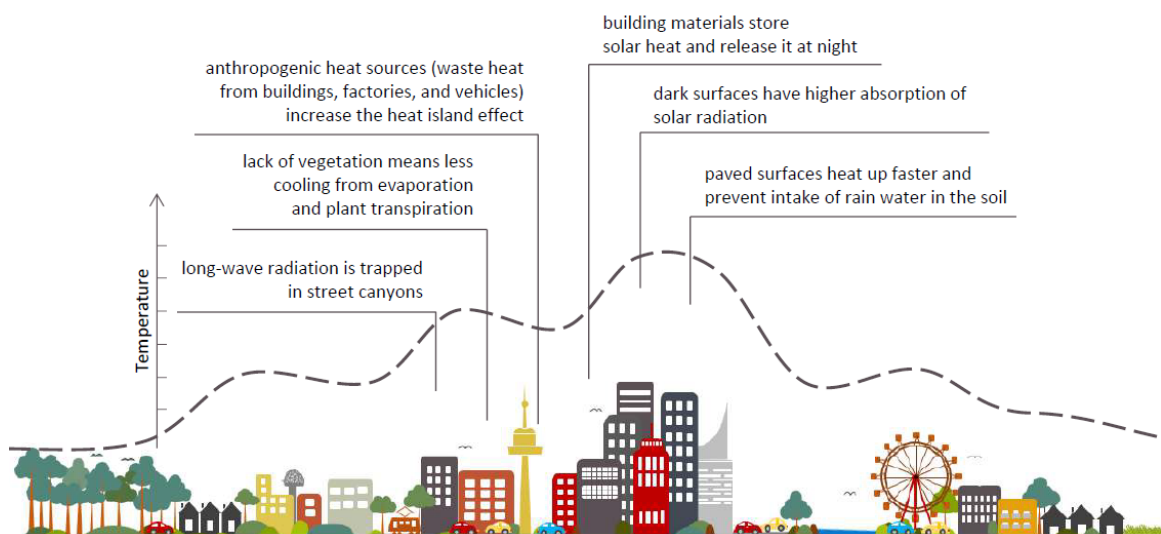


Figure 10: The schematic illustration of UHI effect in urban areas (Bank, 2020)

Urban environment under the influence of social, cultural, economic, infrastructural developments have replaced natural areas with sealed and build up structures. Studies and research (Qian, et al., 2022) (Wang, et al., 2022) are conducted on urbanisation and its influence on weather extremes like Urban Heat Island effect, flash floods, combined sewer flow etc. Correlation between urbanisation, increased rate of precipitation and flash floods has been studied recently in many papers (Wang, et al., 2022) (Qian, et al., 2022). Studies shows that urbanisation results in irregular summer precipitations in cities, even though variation can occur depending on factors like topography, underneath surface characteristics etc (Wang, et al., 2022).

### **3.5. Green buildings focussing Stormwater management.**

Recent studies show that a several fold increase in occurrence, severity, duration of extreme weather events in future. Here comes the importance of stormwater management. By focusing on stormwater management strategies in urban areas, the heavy overflow or run off (explained in section 3.4.1) can be reduced or delayed and hence effects like soil loss and CSO can be reduced to a large extend. Also, if the excess stormwater is stored wisely, it can also be used in dry seasons and can reduce the effects of droughts (explained in section 3.4.2) in urban cities. Improving the features like retention and detention in cities obviously reduces heat waves and stress (explained in section 3.4.3) in cities and aids in improving public health and ecosystem.

Another key justification for concentrating on stormwater management is that only 3% of the total volume of water is potable, whereas 97% of it is sea water. The need of stormwater management solutions is further evidenced by the rise in population and water consumption rates, significant groundwater extraction followed by a discernible decline in the groundwater table, pressure on municipal water supplies for gardening and other uses. Conventional stormwater management techniques are costly, unstable and hence green buildings are emerging more common now adays (How to Increase Water Efficiency in Green Buildings?). Green buildings are environment friendly infrastructures that aid in making a positive effect on ecosystem in its different stages of life span from planning, designing, building and operation stage and avoiding detrimental effects to nature. It focuses on using renewable energy, better technological aspects, preventing waste of natural resources, better indoor air quality, better construction elements focussing on environmental aspects as well (How to Increase Water Efficiency in Green Buildings?).

The major focuses of green buildings are water conservation and water efficiency. Water conservation aims at reducing the usage of water and prevents its wastage, whereas water efficiency focuses on using less water instead of managing without it. It reduces the usage with the help of modern technologies and with the help of digitalisation. Green infrastructures imitate the nature by using soil, vegetation to infiltrate, evapotranspire and recycle rainwater (Ulusoy & Saygin, 2011). It also focuses on decentralised approach aiming at controlling runoff at or near the source by using natural hydrology and increasing infiltration, evapotranspiration retention and detention.

The roles played by green buildings in stormwater management (Tanyanyiwa & Juba, 2018)

- helps in preserving natural water cycle.
- helps in saving the natural hydrological system of a site by retaining and detaining the storm water, infiltration and ground water recharge of the catchment area.
- minimises the contaminants in rainwater.
- improves infiltration rate.
- minimises load on municipal water supply.
- reduces pressure on sewage system and treatment plants at the time of heavy rainfall, by reducing peak flow and by increasing the time of concentration.

Importance of stormwater management in urban areas have been researched in many papers (Saygin & Ulusoy, 2011) (Tanyanyiwa & Juba, 2018). A transformative step of urban stormwater management strategies is highly needed in this era of heavy and excessive precipitation. Studies were also conducted in analysing the challenges faced while implementing stormwater management strategies in urban areas and to identify various strategies that can be used to implement stormwater management techniques (Bohman, Glaas, & Karlson, 2020). Green buildings and their importance in stormwater management techniques in urban areas were studied in various research papers. Different strategies, their advantages and challenges were also discussed with the help of different case studies in various papers (Saygin & Ulusoy, 2011) (Tanyanyiwa & Juba, 2018).

### **3.6. Green building components**

Even though there are many green building components existing, the study mainly focuses on components like green roofs, purple roofs, rainwater harvesting tanks and green spaces in detail.



### 3.6.1. Green roofs

Green roofs are vegetation layer on the top of the roof with sufficient substrate layer for water retaining and detaining purposes. It is mainly of two types: extensive green roofs with shallow depth with a maximum depth of 150mm and intensive green roofs with deeper soil medium greater than 150mm and higher retention capacity around 75%. The transport of water in a green roof has mainly horizontal and vertical component. Green roofs are usually made with high infiltration capacity, hence vertical movement happens first and when it reaches a particular level horizontal water transport happens along the drainage layer near to the surface of roof (Zakrisson, 2019).

Traditional green roofs offer only retention, whereas purple roof concept offers both retention and detention. The process of retention and detention of green roof buildings are explained in section 3.3.4. The Figure 11 below shows the major differences between traditional green roofs and purple roofs.

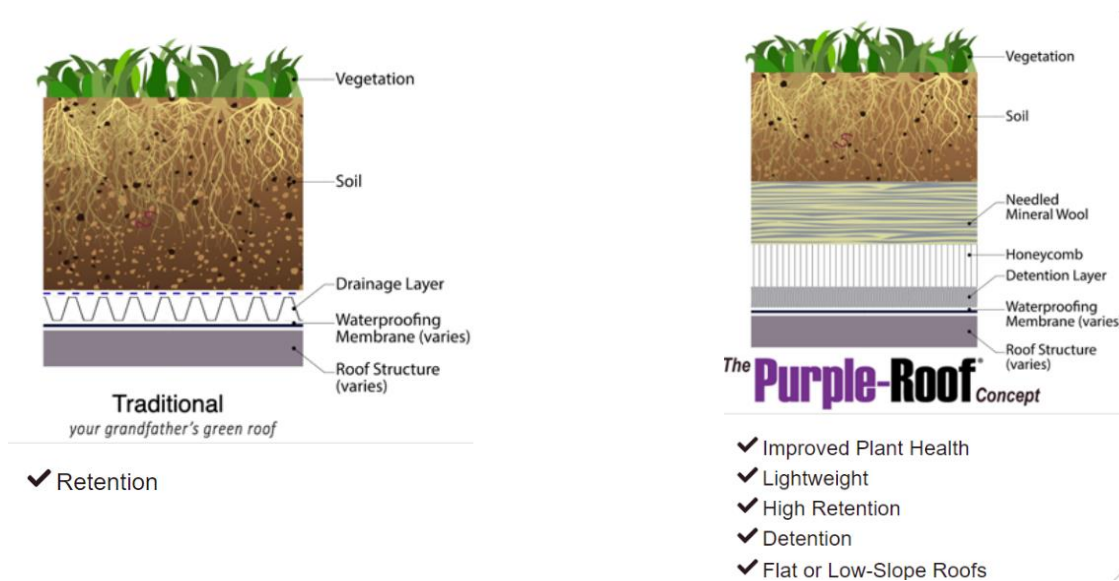


Figure 11: Concept of a) Traditional green roof and b) purple roof (The Purple roof concept, 2023)

In purple roof, the drainage layer in traditional green roofs is replaced by detention layers in the form of honeycomb, which has the capacity to delay runoff by 8-24 hours. When rain reduces, the process of evapotranspiration happens. The ET rate in purple roofs is at a slower rate compared to traditional roofs and hence plants will be stronger and has less watering demands compared to traditional green roofs (Zakrisson, 2019). Purple roof concept is a slight change in blue-green concept which has a fabric mat below the storage layer with a

friction layer as densely spaced polyester threads. The vertically arranged tubes act as a honeycomb and provide extra storage facility. These two components provide a friction or resistance for the drainage throughout the profile (Garner, Jeffers, Hidalgo, Daoularis, & Warmerdam, 2022). Figure 12 below shows different layers of purple roof concept-vegetation layer, growing soil medium, needled mineral wool, honeycomb reservoir layer and friction layer made of polyester.



*Figure 12 :Different layers of purple roof concept (Detention roof, 2023)*

Green roof and their influence in stormwater management in urban areas has been studied in various research papers (Tanyanyiwa & Juba, 2018) (Saygin & Ulusoy, 2011). As the flow length of the roof increases and slope decreases the runoff coefficient is found to be decreasing for a 100-year rain event from 30% to below 10%. The surface runoff is found to be dependent on the local climatic factors, substrate material and its pore volume (Förster, Westerholt, Kraft, & Lösken, 2021). The plant type used in the green roof, its canopy structure, size, density, leaf morphology, root structure etc are found to have an influence on interception and hence on runoff from the roof of green buildings. Species with better ET offers better stormwater retention capacity. The major climatic conditions that affect the evapotranspiration rate are solar radiation, air temperature, humidity, wind speed etc. Even though the rate of ET is higher in hot climates, the ranking of plant species is found to be same in all climatic conditions (P., T., & S. Kemp, 2019).

When the hydrologic behaviour of green roofs was studied, it was seen that the total depth of storm events and length of antecedent dry condition has an influence on the retention capacity of green roofs. In the wet season (winter period) the green roofs showed to be difficult to retain more storm water (Schultza, Sailorb, & Starrya, 2018). Hence in whole, the hydrological response of a green roof mainly depends on configuration of green roof

(include material and build up), geometry of the roof (size, shape, and slope), meteorological conditions and type of plant used. For the design of the excel calculation model, the above factors were considered.

The detention behaviour of green roofs can be increased by rising the depth of growing medium, reducing hydraulic conductivity, using high friction textile mats, increasing distance to the outlet, by decreasing the slope, (Johannessen, Muthanna, & Braskerud, 2018). The vegetated green roofs help not only in reducing the amount of rainwater, but also in increasing its duration over a time period beyond the actual storm event. Among the different factors that helps in improving the retention capacity of vegetated roofs, combination of reduced slope and deeper soil medium helps in minimising the quantity of runoff (Vanwoert, Rowe, Andresen, & Rugh, 2005).

### **3.6.2. Rainwater harvesting tank.**

The main objective of green buildings is to reduce the use of treated water for cleaning and other gardening purposes. By which the cost and energy required for the treatment purposes can be minimised to certain level (Baetz & Guo, 2007). One of the best methods is to have a rain barrel for small projects or cisterns for bigger projects. The local meteorological conditions must be analysed well for calculating the volume of the rainwater harvesting tank. The rainfall characteristics like depth, duration, minimum interval time etc must be taken into consideration. Size of the tank hence depends on area of roof, desired rate of usage of water and the local climatic conditions (Baetz & Guo, 2007). The major functions of the rainwater harvesting tank includes storage of excess rainwater, water supply at the time of demand, control of discharge flow into sewer network (Kim Y. , Kim, Park, & Han, 2014).

### **3.6.3. Green spaces**

Increase in sealed areas due to rapid urbanisation has resulted in severe flooding during heavy rain events. The combination of intense rainfall and large proportion of impervious area results in large volume of surface runoff to the main sewer network within a small-time span. Conventional storm management strategies focus on immediate removal of runoff from cities rather than allowing it to infiltrate down into the soil before leaving it to a water body. But in green infrastructure, focus is on decentralised approach with maximum opportunity to infiltrate down into the soil. The permeability of the underlying soil below the green space also plays a major role in reducing surface runoff (Bai, Mayer, Shuster, & Tian, 2018).

The permeable land cover includes green spaces, meadows, lawns, forest, farmlands, pastures, undeveloped area, bare soil etc. On the other hand, the impermeable category includes streets, roads, developed urban area, sealed areas, pavements, driveway, roofs, parking areas, commercial areas etc. The runoff generated is highly influenced by the land use cover and properties of the soil underneath (Bai, Mayer, Shuster, & Tian, 2018).

Land cover usage like forests, agricultural uses and urban development has the major control over surface runoff. Research shows that the green spaces allow to infiltrate water and to remove it to the atmosphere in the form of ET or drains away as baseflow and results in groundwater recharge. The benefits of vegetated land are water infiltration, soil storage, groundwater recharge, pollutant removal and runoff minimising (Zhang, Xie, Na Li, & Wang, 2015). Tree belts has the capacity to minimise the runoff from a grass slope by 32% - 68% for a 10-year storm event and also by about 100% for a one-two year event. With the increase of about 10% in tree cover in a highly densified area, the surface flow can be reduced by 5.7% for a 28 mm event (Zhang, Xie, Na Li, & Wang, 2015). Some of the green infrastructure in cities include street trees, city parks, vegetated swales, raingardens, other green areas. Research has proven that the different implementations of green spaces in cities has the capacity to reduce runoff from 3%-47%. The reduction rate but depends on level of implementation, land coverage, the intensity of storm event (Zhang, Xie, Na Li, & Wang, 2015).

#### **3.6.4. Permeable pavements**

One of the major reasons behind stormwater runoff in cities are large areas of asphalt or concrete pavements, driveways, parking lots and streets. Permeable pavements provide almost same characteristics of classical paving materials and allows rainwater to infiltrate down into the reservoir. Permeable pavements are usually built over a reservoir made of stone or gravel, that helps as a storage unit and also acts as a filtering unit before sending the water to drain into the subsoil. Sometimes a fabric with the filtering quality is placed below the gravel storage unit which could screen out even fine particles (Cook, 2007). The various types of permeable paving substances are pervious concrete, pervious asphalt, permeable pavers etc. The storage capacity of the system can be increased by improving the size of the stone reservoir or installing pipes on the top of the reservoir to take away overflow at the time of heavy rainfall when the storage tank is full. It helps in removing pollutant

materials from rainwater, reducing the volume of stormwater, lessening the use of curb and gutter, also improving groundwater recharge (Cook, 2007).

### **3.6.5. Vegetated/bio swales**

A vegetated swale is a shallow path with vegetation along its sides and bottom which has the capacity to remove pollutants, promotes infiltration and helps in volume and velocity reduction of stormwater runoff at the time of heavy storm event. They allow for filtering, percolating and eventually minimising the amount of surface runoff in urban cities (Cook, 2007).

### **3.6.6. Bioretention & biofiltration units**

This strategy makes use of vegetation to eliminate contaminants from stormwater runoff. They are often allowed as sheet flow to a treatment area. Runoff is hence allowed to filter, percolate down into ground water or it can also be evapotranspired. Runoff can also be allowed, to be stored in the unit for a longer time and can also be released after the heavy storm event at a slower rate. The system is usually used to store, treat and release stormwater which usually contains large number of pollutants while flowing over sealed urban areas. Its benefit includes improving water quality, reduce peaks and increase concentration time at the time of discharge (Cook, 2007). The Figure 13 below shows the different green building components described above.

This research study considers two catchment areas, the first being the Elementary School located in Schauenstein city. The Elementary School is equipped with the green building components like purple green roof, rainwater harvesting tank, and green spaces. The second catchment area is the Hof University of applied science, which features green building components such as purple green roof and a pre-existing retention pond.



Figure 13: The sketch of different green building elements (Chen & Chen, 2020)

### 3.7. KOSTRA DATA 2020

For the purpose of finding the probability of occurrence of heavy storm events in Germany, the Deutscher Wetter Dienst (DWD) has been making an evaluation for heavy storm along with the coordination of all the federal states of Germany from 1980s. Usually updates are made at every 10 years. After a short time, the new KOSTRA DATA 2020 is officially followed from 01.01.2023 (Deutscher Wetter Dienst, KOSTRA-DWD, 2023).

The major terms used in KOSTRA DATA includes (Deutscher Wetter Dienst, KOSTRA-DWD, 2023):

**Duration (D):** It represents the time period with precipitation. KOSTRA DATA 2020 provides 22 standard durations starting from 5 minutes to 168 hours.

**Recurrence time (T):** the period within which the occurrence of a particular event is anticipated to occur only once. KOSTRA DATA 2020 provides 9 return time starting from 1 a to 100 a.

**Precipitation height:** The maximum value of the precipitation with the statistical analysis of a function of duration and recurrence time. The unit is in millimetre or litre per meter square.

While using the values of precipitation height and rate from KOSTRA-DWD 2020 DATA, it should be kept in mind that there might be a level of uncertainty in the values due to large variability in precipitation at temporal and spatial level, uncertainties in digitalisation of data, in regionalisation, evaluation methodology, statistical estimation and so on (Junghänel, Ostermüller, & Deutschländer, 2022).

## 4. General methodology

### 4.1. Water balance equations

In the simplest form, water balance equation for a catchment area according to law of conservation of mass can be depicted as (European Commission, 2015):

$$\mathbf{Input = Output \pm \Delta S} \quad (1)$$

where input & output = the inflow and outflow of water into/ from the catchment area

$\Delta S$  = change in water storage within the catchment area.

Considering a catchment area with no external flows, precipitation (P) can be considered as the inflow into the zone, which then gets converted into evaporation(E), transpiration(T), runoff (surface, sub surface or groundwater) (R) and change in storage ( $\Delta S$ ) within the considered time period can be depicted using the water balance equation as (European Commission, 2015):

$$\mathbf{P = R + E + T \pm \Delta S} \quad (2)$$

Moving into detail, each component of the water balance equation can again be subdivided into more components. During a given time period, precipitation (P) reaches the surface, water can be intercepted and evaporated ( $E_i$ ) directly from the vegetation on soil surface or can even be stored ( $\Delta S$ ). Water can also be infiltrated down into the soil and when it exceeds the infiltration capacity of the soil it can also start to directly run off (also named as surface run off) ( $R_s$ ). The water that infiltrates down into the soil, can reach the unsaturated zone ( $\Delta S_u$ ) and the ground water zone ( $\Delta S_{gw}$ ). Runoff can happen in unsaturated zone ( $R_{sub}$ ), named as subsurface runoff and in groundwater zone ( $R_{gw}$ ) named as base flow. The vegetation roots have the capacity to absorb water and transport into the leave's stomata, from where it can be evaporated back into the atmosphere named as transpiration ( $E_t$ ). Water can be evaporated directly from soil and other water bodies ( $E_s$ ). Combining all these components, water balance equation can be modelled as (European Commission, 2015):

$$\mathbf{P = R_s + R_{sub} + R_{gw} + E_s + E_i + E_t \pm \Delta S} \quad (3)$$

If there is any kind of inflow into the catchment area, the equation can be expressed as (European Commission, 2015)

$$\mathbf{P + I = ET + Q + \Delta S + \Delta G + \Delta W} \quad (4)$$

where P = precipitation,

I = inflow into catchment area,

ET = evapotranspiration ( $E_s + E_i + E_t$ ),

Q = outflow from the catchment area ( $R_s + R_{sub} + R_{gw}$ ),

$\Delta S, \Delta G, \Delta W$  = water storage in soil (unsaturated zone), groundwater storage (in saturated zone) and in water bodies

Assuming the hypothesis of a catchment area with finite boundaries under stationary meteorological conditions, a storage model of local water including water in root zone, soil profile, groundwater, surface storages could be calculated by integrating a continuous water balance equation with respect to time (Stella, 2019).

$$\frac{dS}{dt} = P - ET - Q \quad (5)$$

where S is water storage in mm,

t is no. of days.

Also, the change in storage  $\Delta S$ , which is the difference between final and initial water storage is the balance between the different elements like evapotranspiration, runoff, precipitation and an extra residual factor which includes the errors in measuring rainfall, runoff and evapotranspiration, groundwater storage, surface storages etc. Depending on the direction of flow, the factor can be positive or negative (Stella, 2019).

$$\Delta S = S_f - S_o = P - ET - Q - R \quad (6)$$

When all the components are expressed in a series in function of time, the relative water storage at time step i can be expressed as (Stella, 2019):

$$\Delta S_i = S_i - S_{i-1} = P_i - ET_i - Q_i - R_i \quad (7)$$

Making a summation of all the parameters (Stella, 2019),

$$S_f - S_o = \sum_0^n \Delta S_i = \sum_0^n \Delta P_i - \sum_0^n \Delta ET_i - \sum_0^n \Delta Q_i - \sum_0^n \Delta R_i \quad (8)$$

where n is the number of steps (Stella, 2019)

$$S_f = S_o + \sum_0^n \Delta P_i - \sum_0^n \Delta ET_i - \sum_0^n \Delta Q_i - \sum_0^n \Delta R_i \quad (9)$$

where P, ET, Q, R are the average precipitation, evapotranspiration, runoff and residual during n time steps.



## 4.2. Runoff equations

Different methods are there to calculate peak discharge runoff from a catchment area.

### 4.2.1. Empirical formulae

- a. Formulae like Dickens, Ryves, Ingles, considers only area of the catchment ( $Q=CA^n$ ) (Ven Te Chow, 2007)

- Dickens Formula:  $Q_p - CA^{3/4}$  (10)

- Ryves Formula:  $Q_p - CA^{2/3}$  (11)

- Ingles Formula:  $Q_p - 123 \cdot A^{1/2}$  (12)

where  $Q_p$  is the peak discharge runoff from the catchment area in  $m^3/s$

$A$  is the area of catchment in  $km^2$ ,

$C$  is the coefficient of discharge of the area

- b. Other elements like intensity, depth or maximum rainfall along with area of the catchment area are used in formulas like Craig, Lillie and Rhinds (Ven Te Chow, 2007)

- Craig formula:  $Q = 10 \cdot k \cdot B \cdot v \cdot I \cdot \ln((4.97 L^2) / B)$  (13)

where  $Q$  is peak discharge in  $m^3/s$ ,

$k$  is runoff coefficient,

$B$  is the average width of catchment in km,

$v$  is velocity of runoff in m/s,

$I$  is average rainfall intensity in cm/hr,

$L$  is greatest length of catchment in km

- Lillie's Formula:  $Q = 0.058 \cdot V \cdot R \cdot k \cdot \sum \theta \cdot L$  (14)

where  $Q$  is discharge in  $m^3/s$ ,

$V$  is velocity of flow m/s,

$R$  is rainfall coefficient given by ( $R=2+(p/38.1)$ ),

$k$  is coefficient ( $0.8934+\log L$ ),

$\theta$  is apical angle and  $L$  is length in km.

- Rhinds Formula:  $Q = 0.098 \cdot C \cdot S \cdot R \cdot (0.386 A)^p$  (15)

where  $Q$  is discharge in  $m^3/s$ ,

S is average fall of last 5 km of the river above the basin outlet in m/km,

R is greatest average annual rainfall in cm,

p is variable index,

L is greatest length of catchment in km,

C is coefficient depends on R/L.

- c. Some of the formulas consider recurrence interval into consideration (Ven Te Chow, 2007).

- Fullers Formula:  $Q = CA^{0.8}$  (16)

$$Q = Q_{av}(1 + 0.8 \log T_r) \quad (17)$$

where Q is maximum 24 hour flood,

A is basin area in sq km,

$T_r$  is return period in years,

C is coefficient varies from 0.026 to 2.77

- Hortons formula:  $Q = \frac{114 T_r^{0.25}}{A}$  (18)

where Q is flood discharge in cumec

- Pettis formula:  $Q = C(PB)^{5/4}$  (19)

where Q is flood discharge with return periods of 100 years in cumec.

C is coefficient varying from 1.51 in humid areas to 0.195 in desert areas

P is one day rainfall with 100 years return period in cm

B is average width of basin in km

#### 4.2.2. Using rational method

The peak value of discharge  $Q_p$  can be obtained by the formula (Ven Te Chow, 2007).

- $Q_p = 2.78 * C * i_{tc,p} * A$  (20)

where C = coefficient of runoff (runoff/rainfall)

A = area of catchment in  $km^2$

L = maximum length of water travel in m

S= slope of catchment =  $\Delta H/L$

$\Delta H$ = difference in elevation between most remote point and outlet.

$i_{t_c,p}$ = intensity of rainfall in cm/hr for a duration  $t_c$  and an exceedance probability P

$$i_{t_c,p} = \frac{KT^x}{(t_c+a)^n} \quad (21)$$

$t_c$ = time of concentration (Ven Te Chow, 2007)

$$t_c = \frac{0.0194L^{0.77}}{S^{0.385}} \quad (22)$$

Rational method requires four parameters to obtain the maximum runoff from a catchment area  $t_c$ , C,  $i_{t_c,p}$  and A

#### 4.2.3. SCS-CN method

The method was developed in 1969 by the Soil Conservation Services (SCS) of USA. It is a very simple conceptual method to find out the runoff depth from a rainfall depth. It requires only one parameter CN. It is a method based on water balance equation of rainfall for a time period of  $\Delta t$ . It can be expressed as (Mishra & Singh, 2003)

$$P = I_a + F_a + P_e \quad (23)$$

where P=total precipitation

$I_a$ = initial abstraction

$F_a$ = cumulative infiltration excluding  $I_a$

$P_e$ = direct surface runoff

For small catchment areas (Mishra & Singh, 2003)

$$P_e = \frac{(P-0.2S)^2}{P+0.8S} ; \text{ for } P > 0.2S \quad (24)$$

$$CN = \frac{25400}{S+254} ; \quad (25)$$

CN ranges from 0-100. CN =100 represents zero retention which is a impervious catchment CN=0 represents a highly pervious catchment where  $S=\infty$ .

CN depends on many factors like soil type, antecedent moisture content and land use/cover type.

#### 4.2.4. Unit hydrograph method

The method was first developed by L.K. Sherman in 1932 and it is till now one of the simplest tools in hydrology. A unit hydrograph is obtained from a characteristic hydrograph of a catchment area obtained by a unit depth of uniformly distributed rainfall over a unit duration time. Unit hydrograph method is suitable for medium sized catchment areas up to 5000 sqkm. For larger areas, the catchment area must be divided into sub basins and for each sub basin unit hydrographs must be considered. Area under the unit hydrograph is known as unit volume. It is created by unit depth of rainfall over the catchment area (US, 1973).

$$\text{Unit volume} = 1\text{cm} * \text{catchment area} \quad (26)$$

#### 4.3. Evapotranspiration

To estimate the irrigation demands of an area, it is well essential to find out its evapotranspiration rate. Different analytical equations and simple empirical equations are used to find out the PET rate of an area. Each of these methods use different variables and use different weightage on the variables. Some equations depend on maximum, minimum and average temperature of the catchment area, whereas some others depend on incoming solar radiation, wind velocity, daylight hours etc. Major methods to estimate ET rate are listed below:

##### 4.3.1. Penman- Monteith (1965)

It is a well-known equation formed by the combination of an energy balance and an aerodynamic formula. The original equation in 1948 has been modified in 1965 (Howell & Evett, 2004).

$$\lambda ET_0 = \frac{\Delta(R_n - G) + \frac{86400 \rho_a C_p (e_s - e_a)}{r_{av}}}{\Delta + \gamma \left(1 + \frac{r_s}{r_{av}}\right)} \quad (27)$$

where  $ET_0$  reference evapotranspiration

$R_n$  net radiation at the crop surface

$G$  soil heat flux density

$\rho_a$  = air density in  $\text{kg/m}^3$

$C_p$  = specific heat of dry air in  $1.013 \times 10^{-3} \text{ MJ/kg/C}$

$e_s$  saturation vapour pressure in KPa

$e_a$  actual vapour pressure in KPa

$e_s - e_a$  saturation vapour pressure deficit

$\Delta$  = Rate of change of saturation specific humidity with air temperature.

$\gamma$  = psychrometric constant

$r_s$  = canopy surface resistance in s/m

$r_{av}$  = bulk surface aerodynamic resistance for water vapour in s/m

#### 4.3.2. FAO 56 Penman- Monteith (1998)

In order to avoid the complexity in the Penman Monteith equation, the Food and Agricultural Organisation has modified the equation to simplify it. It is one of the most commonly used equation to find out reference evapotranspiration rate. The equation is developed on energy balance of land surface and it includes various variables like temperature, humidity, solar radiation, wind speed etc (Mishra & Singh, 2003).

$$ET_0 = \frac{0.408\Delta(R_n - G) + \frac{\gamma 900}{T_a + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (28)$$

where  $u_2$  wind speed at 2 m height

#### 4.3.3. Thornthwaite method (1948)

In this method evapotranspiration is calculated using temperature and latitude. It is calculated using a simplified equation considering temperature variation and length of the day (Mishra & Singh, 2003).

$$ET_0 = ET_{osc}(N/12)(dm/30) \quad (29)$$

$$ET_{osc} = 16(10T_a/I)^a \quad (30)$$

where  $ET_0$  = potential evapotranspiration

$ET_{osc}$  = gross evapotranspiration

$N$  = maximum number of sunny hours in a function of month and latitude

$dm$  = is the number of days per month

$T_a$  = mean daily temperature in  $^{\circ}C$

$I$  = annual heat index

$a = 0.49239 + 1792 * 10^{-5} I - 771 * 10^{-7} I^2 + 675 * 10^{-9} I^3$ , which is an exponent

#### 4.3.4. Hargreaves equation (1985)

It is a simplified version of Penman-Monteith method that helps to estimate evapotranspiration using temperature and solar radiation of the area (Cascone, Comab, Gaglianoc, & Perezd, 2019).

$$ET_0 = 0.0022R_s (T_{\text{mean}} + 17.8) (T_{\text{max}} - T_{\text{min}})^{0.5} \quad (31)$$

where  $R_s$  = extra-terrestrial radiation in MJ/m<sup>2</sup>day (Stefferud, 2016)

$$R_s = \frac{26 \cdot 60}{\pi} G_{sc} d_r (\omega_s \sin(\psi) \sin(\delta) + \cos(\psi) \cos(\delta) \cos(\omega_s)) \quad (32)$$

$d_r$  = inverse relative distance between earth and sun (Stefferud, 2016)

$$d_r = 1 + 0.033 \cos \frac{2\pi J}{365}; \quad (33)$$

J= Julian day

$\psi$ = latitude of location in radians

$\delta$ = solar declination (Stefferud, 2016)

$$\delta = 0.409 \sin \left( \frac{2\pi J}{365} - 1.39 \right) \quad (34)$$

$\omega_s$  = sunset hour angle (Stefferud, 2016)

$$\omega_s = \arccos (-\tan \psi \cdot \tan \delta) \quad (35)$$

$T_{\text{mean}}$ ,  $T_{\text{max}}$  and  $T_{\text{min}}$  = Average, maximum and minimum daily temperature in °C

#### 4.3.5. Priestly Taylor method

It is mainly based on energy balance of the land surface and uses only temperature and solar radiation as the variables to obtain evapotranspiration (Cascone, Comab, Gaglianoc, & Perezd, 2019).

$$ET_0 = \alpha \Delta (R_n - G) / (\Delta + \gamma) \quad (36)$$

where  $\alpha$  is a constant for vapour pressure deficit usually takes value of 1.26.

All other variables are similar as used in Penman Monteith equation.

#### 4.3.6. Blaney Criddle method

Here evapotranspiration is calculated with the help of temperature and humidity of the area. It is a very simple and quick procedure often used when more data is not available (Mishra & Singh, 2003).

$$ET_0 \text{ (mm/day)} = p \times (0.46 T_{\text{mean}} + 8) \quad (37)$$

where p= mean daily percentage of annual daytime hours.

#### 4.3.7. Lysimeter method

It is done by measuring the amount of water evaporated from a small area, which is enclosed inside a container. It gives the exact measurement of evapotranspiration, but the setup is

difficult to build up. Lysimeter is one of the common equipment used to measure evapotranspiration. The equation below is used to calculate evapotranspiration using Lysimeter method. Figure 14 below shows the representation of soil water balance in weighing Lysimeter (Cascone, Comab, Gaglianoc, & Perezd, 2019).

$$ET = P - D - O \pm \Delta S \quad (38)$$

where ET is evapotranspiration in mm

P is precipitation depth in mm

D is Drainage

O is superficial runoff

$\Delta S$  is the change in soil water storage.

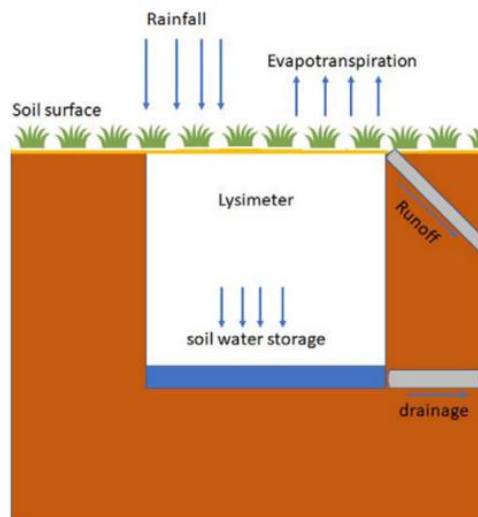


Figure 14: The schematic representation of soil water balance in weighing lysimeter (Cascone, Comab, Gaglianoc, & Perezd, 2019)

#### 4.3.8. Water balance method

In this method evapotranspiration is estimated based on water balance model of the catchment area. Precipitation of the catchment area and factors like runoff, and storage is calculated as input. The difference between the values gives the evapotranspiration value (Stefferd, 2016).

$$ET = P - R - \Delta S \quad (39)$$

where ET is evapotranspiration in mm

P is precipitation in mm

R is the runoff in mm

$\Delta S$  is storage in mm.

For the study, Hargreaves equation is chosen, since the equation is found to be reliable and its simple and easy to use with important factors. The above reference evapotranspiration is then multiplied with water stress coefficient and crop coefficient, to obtain the actual evapotranspiration (Vanuytrechta, et al., 2014)..

$$\mathbf{ET = PET * K_s * K_c} \quad (40)$$

where  $K_s$ = water stress coefficient

It varies from 0 (full stress at extreme dry climate), when the soil moisture content is zero till 1 (no stress). Zero stress level might not be attainable, but efforts should be made to reduce the stress level in a catchment area. The stress level can be obtained by the equation below (Vanuytrechta, et al., 2014).

$$\mathbf{S=100 * (1-(WS_{act}/(p*WS_{max})))} \quad (41)$$

where  $S$ = stress level

$P$ = threshold for vegetation stress

$WS_{max}$ = maximum amount of water retained on roof

$WS_{act}$ = actual amount of water retained on roof

$K_c$ =crop coefficient

Crop coefficient depends on the type of vegetation used or how easily water can be evaporated from an area.

#### **4.4. Change in storage**

Water storage in soil plays a major role in the water balance of a catchment area. The process by which water enters soil is referred as infiltration. The infiltrated water is then stored in the substrate depth. The maximum amount of water which a soil can absorb at a given condition is termed as its infiltration capacity. Whenever the infiltration capacity is exceeded, it results in surface runoff. The hydraulic conductivity and water retention capacity of the soil plays a major role in infiltration rate. Different methods are there to find out the infiltration rate of a catchment area (Liu, Engel, & Feng, 2021).

##### **4.4.1. Horton infiltration method**

For a given rain, the infiltration rate decreases with time. At the beginning of the rain, the rate tends to show a maximum and then decreases gradually with time until it reaches a constant value (S.C. Verma, 1982).



$$f_p = f_c + (f_o - f_c)e^{-kt} \quad (42)$$

where  $f_p$  = infiltration capacity in mm/hr at any time  $t$

$f_o$  = initial infiltration capacity in mm/hr

$f_c$  = final infiltration capacity at saturation

$t$  = time in hours from rainfall beginning

$K$  = exponential decay constant.

#### 4.4.2. The $\phi$ index method

The simplest method, the  $\phi$  -index, determines infiltration as the difference between measured surface runoff and gross rainfall. The loss is thought to be evenly distributed throughout the pattern of rainfall (Sraj, Dirnbek, & Brilly, 2010).

#### 4.4.3. Philip method

Philip method has suggested a formula to calculate infiltration  $F(t)$  by (J.S.C. Mbagwu, 1994)

$$F(t) = St^{0.5} + Kt \quad (43)$$

where  $S$  = sorpivity, a function of soil suction head

$K$  = hydraulic conductivity of soil

$t$  = time from beginning of rainfall

#### 4.4.4. Green Amt method

It is an estimation method which is based on Darcy's law. The method is developed on the assumption that water is ponded in the soil for a depth  $d$ , then maximum soil water storage is defined as (Liu, Engel, & Feng, 2021):

$$F(t) = L(\theta_{FC} - \theta_{WP}) \quad (44)$$

where  $L$  = substrate depth in mm

$\theta_{FC}$  = field capacity of the soil

$\theta_{WP}$  = permanent wilting point of the soil

The permanent wilting point and field capacity varies from soil to soil. The Table 2 below shows the approximate field capacity and permanent wilting point of different type of soils.

Table 2: Soil water characteristics for different soil types (Allen, Pereira, Raes, & Smith, 1998)

Soil type	Field Capacity ( $\theta_{FC}$ )	Permanent wilting point ( $\theta_{WP}$ )
Sand	0.07-0.17	0.02-0.07
Loamy sand	0.11-0.19	0.03-0.1
Sandy loam	0.18-0.28	0.06-0.16
Loam	0.2-0.3	0.07-0.17
Silt loam	0.22-0.36	0.09-0.21
Silt	0.28-0.36	0.12-0.22
Silt clay loam	0.30-0.37	0.17-0.24
Silty clay	0.30-0.42	0.17-0.29
clay	0.32-0.40	0.20-0.24

Even though there are different methods to calculate storage capacity or retention capacity of the area, for the particular study, retention storage of the purple roof is taken directly from the manufacturers (Sempergreen).

#### 4.5. Volume of rainwater harvesting tank

According to British standard Rainwater harvesting system code of practice BS 8515:2009, to calculate the volume of a rainwater harvesting tank, three approaches are mentioned (British standards, 2009).

1. Simplified approach, mainly used for residential buildings with fixed daily demand.
2. Intermediate approach, for commercial buildings like schools, offices etc.
3. Detailed approach, where variable demands are observed over the year.

The intermediate approach is used in the calculation model to find out the storage volume of the rainwater harvesting tank. The method suggests that the storage capacity can meet the non-potable water demand, if its volume is the lesser value of either 5% of annual yield or 5% of non-potable water demand.

$$\text{5\% of Annual rainwater yield from roof} = A * e * AAR * h * 0.05 \quad (45)$$

where  $A$  = area of roof in  $m^2$

$e$  = runoff coefficient (0.9 for normal pitched roofs)

$AAR$  = site specific annual average rainfall in mm

$h$  = filter efficiency (assumed as 0.95)

$$\text{5\% of annual non potable water demand in litres} = Pd * 365 * 0.05 \quad (46)$$

where  $Pd$  = daily non potable water demand in litres.

## 5. Applied methodology

### 5.1. Site visit

A site visit has been made to the Elementary school of Schauenstein, the first catchment area and the nearby areas have been studied carefully. The school is situated in the downside of a slope where the upper region are green fields which can be seen in the below image clearly. At the time of heavy precipitation events, there is a chance of runoff from these slopes down towards the city. Figure 15 below shows the same near to the school building. Residential and commercial buildings are there around the school building. There is a green open space in front of the school building.

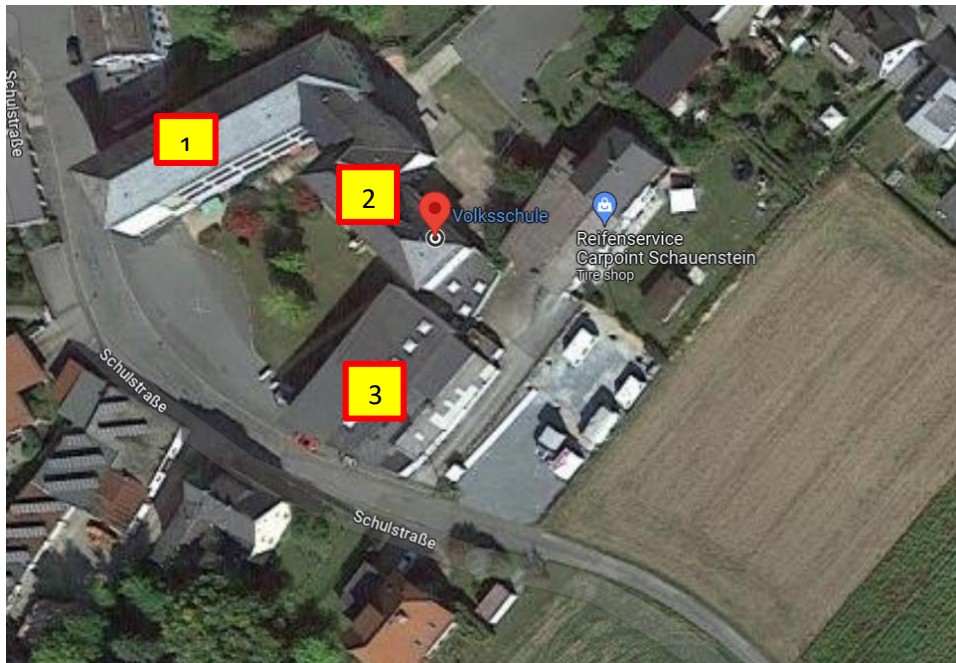


*Figure 15: Slopy land near to School building*

### 5.2. Water balance model

The Schauenstein Elementary School campus was meticulously examined to implement the water balance model. The campus was separated into three main buildings, the water balance

model was applied separately to each structure. The Google image of the school building with its three primary building characteristics is depicted in the Figure 16 below.



*Figure 16: Schauenstein elementary school with the three main buildings (google map image)*

The 1 and 2 buildings are simple plain roofs without any vegetation over them. Hence it does not have contribution towards evapotranspiration and storage as that of a green roof. The water balance components ET and  $\Delta S$  is assumed to be zero for the 1 and 2 building structures. Hence for the buildings 1 and 2, input precipitation over them is assumed to be fully converted into runoff.

For the building 3, where a purple green roof is suggested, the water balance components like evapotranspiration and water storage is involved. Purple roof is a new kind of green roof which works on the principle of both retention and detention as explained in section 3.6.1. The retention capacity is mainly driven by the evapotranspiration of the green roof along with its storage capacity. The calculation sheet can also be used for determining water balance of other catchment areas as well. For the preparation of the calculation sheet following steps are used:

1. Determine the size and characteristics of the green roof: The area and slope of the green roof, the type of vegetation, soil depth, its field capacity, permanent wilting point, and drainage layer all affect how much water the roof can retain and how much will run off.

2. Calculate the water input: The water input to the green roof includes rainfall, irrigation, and any other water sources. The average rainfall in the study area is taken from historical data and how much water falls on the green roof is estimated using area of the roof.

3. Calculate the water retention & detention of the green roof: The water retention of the green roof depends on the vegetation and soil characteristics. The water holding capacity of the green roof can be measured by measuring the water content of the soil at field capacity and at wilting point. The water holding capacity is the difference between these two values. The detention volume of the green roof has to be obtained from the manufacturers of the green roofs and it depends on the profile of the purple green roof.

4. Calculate the evapotranspiration: Evapotranspiration is the process by which water is lost from the green roof through evaporation and plant transpiration. It can be estimated by using actual evapotranspiration data, which is based on weather data such as temperature, humidity and solar radiation, plant stress coefficient and crop coefficient.

5. Calculate the runoff: The runoff is the water that is not retained or evaporated by the green roof and flows off the roof. Runoff can be calculated as the difference between the water input and the water retained or evaporated by the green roof.

Seps 1-5 are explained in detail below:

Input precipitation on the roof was calculated by the following equation (Inc., 2007) (Kim T. , Kim, Park, & Han, 2014)

$$W_{in} = R_{obs} * \Omega * \text{Collection efficiency} \quad (47)$$

where  $R_{obs}$  = rain observed in mm/day taken from DWD data

$\Omega$  = surface area of roof in  $m^2$

90% collection efficiency is assumed to have for normal pitched roofs and 100% for green roofs.

The reference evapotranspiration of the purple roof from building 3 was calculated using Hargreaves equation 31. The minimum, maximum temperature, daily precipitation of Schauenstein region were taken from Climate Data Centre of Deutscher Wetter Dienst (Deutscher Wetter Dienst, Klima Data, 2023). Crop coefficient  $K_c$  being an important factor was assumed to be 0.56 for Sedum plant (The Purple roof concept, 2023). Plant stress coefficient  $K_s$  will always be a value between the 0 -1 (The Purple roof concept, 2023). For rain events, it was assumed that the water level will be above the threshold value and hence

$K_s$  will be equal to 1 for the months except July, August and September. Actual evapotranspiration was then calculated using Equation 40 above. Evapotranspiration from the roof of building 3 was found out using below equation.

$$ET = AET * \Omega \quad (48)$$

where AET = actual evapotranspiration roof from equation 40

$\Omega$  = surface area of roof of building 3

The maximum water retention capacity of the green roof depends on the depth of the substrate, its field capacity and permanent wilting point as in Green Amt method equation 44. The permanent wilting point and field capacity will be different for different soil types as shown in Table 2 above. But for the calculation model, the maximum storage retention capacity of the green roof has been taken from the Sempergreen, manufactures of the purple roof as 33 mm and detention storage of about 57 mm for a purple roof of soil medium about 40mm depth.

Using water balance equation in equation 4, the water balance model of the green roof can be written as (Poe, Stovin, & Berretta, 2013)

$$\begin{aligned} \text{Runoff} &= P - (S_{\max} - S_{\text{act}}) - ET && \text{if } S_{\text{act}} + P - ET > S_{\max} \\ &0 && \text{if } S_{\text{act}} + P - ET \leq S_{\max} \end{aligned} \quad (49)$$

where P= precipitation

ET= evapotranspiration

$S_{\max}$  and  $S_{\text{act}}$  = maximum and actual water retention capacity.

Maximum runoff that can occur from the purple roof, if the precipitation extends for more days, can be calculated as

$$\text{Runoff} = \text{Precipitation} - \text{Evapotranspiration} - S_{\max} \quad (50)$$

### 5.2.1. Calculation of volume of rainwater harvesting tank

Runoff from the whole Schauenstein Elementary school was taken as the sum of the runoff from the three building properties. For calculating the volume of the tank, the runoff coefficient from purple roofs was assumed to be 40% rather than the 90% applied for normal roofs (Kim Y. , Kim, Park, & Han, 2014) (Mentens, Raes, & Hermy, 2006). The volume of

the rainwater water harvesting tank was also then found with the help of the calculation model using BS 8515:2009 Code of Practise.

### **5.2.2. Calculation of runoff from extreme and normal precipitation event**

From the daily precipitation data from DWD, the region of Schauenstein had experienced maximum rainfall during the storm event on July 13, 2021, which brought about the city's biggest rainfall event between 1972 and 2022. The same calculation table was used to check whether the volume of the rainwater harvesting tank was sufficient for such extreme weather events. If not how much amount of overflow may occur during such events. Additionally, the runoff for a regular precipitation event (17.09.2011) was also checked using the calculation model.

Although the green roof has a retention capacity of roughly 33mm, only 50% of that retention capacity was utilized in the calculation model. According to the literature review (Schultza, Sailorb, & Starrya, 2018), the antecedent moisture situation significantly affects the green roof's capacity to hold water. Hence for the purpose of safety, the rainfall was assumed to be a second day storm in which half of the retention volume was already filled with rainwater. Also, to identify the percentage of detention storage getting filled with a particular rainfall event, it was assumed that for Euler type 2 rain events, maximum runoff happens around 65% of the cumulative rainfall volume and at this time the detention storage reaches its maximum value.

### **5.2.3. Tank for extreme drought events**

A drought event was also considered to determine whether the rainfall collected in the tank is enough to satisfy the green roof's water needs or whether other water input sources are required. As an illustration, the three-week-long drought occurred in July 1976 was taken into consideration. According to data from the CDC-DWD data, the amount of precipitation for the storm event that came before the drought event was 9.8 mm. It is assumed that plant stress is 0.1, which is nearly equal to 0. With the help of these data, the calculation model was used to check whether the rainwater collection tank's water supply is sufficient to meet the water needs of the purple roof or whether additional external sources are required.

### **5.2.4. Tank for 3a, 5a,10a and 100a storm events**

Using KOSTRA-DWD data for the Schauenstein region (shown in section 2.1.3), the utility of the rainwater harvesting tank for storm events in the future was also assessed. The grid

data on the precipitation height, duration and return period was taken from the KOSTRA DATA. The volume of the tank was monitored for the precipitation events over a period of 24 hours with return periods of 3, 5, 10 and 100 years. To test whether the rainwater collection tank is sufficient, the calculating model used the precipitation values from these four events.

#### **5.2.5. Calculation model applied on Hochschule Hof**

On the campus of Hochschule, the same water balance calculation was performed. The main buildings A, B, C, D, E, G (iisys), Einstein Lab building and mobile units were used for the runoff calculations after a thorough analysis of the campus is shown in Figure 5. Buildings A, B, C, E, G (iisys), Einstein Lab building and mobile units were assumed to have purple green roofs with the same profile as that of Schauenstein School. Building D's sloping roof precludes the use of a green roof, hence no vegetation was thought to be present. For the building D, the water balance components ET and  $\Delta S$  are taken to be zero.

The same equation 47 was used to determine the input precipitation on the roof. Using Hargreaves equation 31, the reference evapotranspiration for the purple roof buildings were determined. The meteorological information for Schauenstein and Hof was comparable because the two cities were close to one another. Since the meteorological circumstances and green roof profiles in both cases were similar, the crop coefficient  $K_c$  and plant stress coefficient  $K_s$  were assumed to be identical to that of Schauenstein. Retention and detention storage were similar in both cases because of the same green roof profile.

Based on the maximum rainfall event that occurred on July 13, 2021, the maximum runoff from the roofs was computed from the daily precipitation data from DWD. The retention pond in the front area, which has a volume of  $1200 \text{ m}^3$ , was also tested to see if it has enough capacity to hold the extra runoff water from all the buildings using the excel calculation table. The computation model was also used to assess the runoff for a typical precipitation event. The occurrence during a drought was taken into account to ascertain whether the retention pond's volume was adequate to meet the roof's water needs or whether additional water input sources were necessary. Future storm event utility of the retention pond was also evaluated using KOSTRA-DWD data for the Hof region. Additionally, a comparison of runoff from buildings on the Hochschule campus with and without purple roofs have been done in order to determine the significance of green buildings for stormwater management.



## 6. Results and discussions

### 6.1. Water balance equations

The different equations to apply water balance for a catchment area were compared. The advantages, limitations and requirements of each method are listed below in the Table 3.

Table 3: Comparing different methods to compute water balance in a catchment area.

No.	Equation	advantages	limitations
1	$P = R + E + T \pm \Delta S$	Expressed in simplest form	Does not consider any input flow into the catchment area
2	$P + I = ET + Q + \Delta S + \Delta G + \Delta W$	Expressed in simple form. Considers input flow as well.	
3	$\frac{dS}{dt} = P - ET - Q$		Complex form includes integration
4	$S_f = S_o + \sum_0^n \Delta P_i - \sum_0^n \Delta ET_i - \sum_0^n \Delta Q_i - \sum_0^n \Delta R_i$	Considers residual errors as well	Complex form includes integration

From the above comparison, the equation 2 is the simplest one, considering input flow as well. The same equation is hence used to apply water balance modelling for the selected green buildings and its surrounding premises. The calculation model developed in excel, using the major components involved in the water balance of the green building and its nearby premises that can control the surface runoff from the property, is worked on the basis of this equation.

### 6.2. Runoff equations

Different methods to estimate peak runoff from a catchment area were studied and compared. The identified advantages, limitations and requirements of each method are listed below in the Table 4.

Table 4. Different methods to estimate peak runoff from a catchment area.

<b>Method</b>	<b>advantages</b>	<b>limitations</b>	<b>requirements</b>
Empirical formula (Ven Te Chow, 2007)	It needs only few parameters and is simple to use. It can be used in different catchments, provided that the coefficients are calibrated to local conditions.	It has limited accuracy than other methods.	Area, length and width of the catchment, maximum rainfall intensity, flow velocity, coefficients of the catchment
Rational method (Fantina, 2012)	It provides quick results, and it is useful for preliminary flood risk assessments. It is useful to find out peak flow discharge which can be used for the design of urban drainage, small bridges and culverts	It is applicable only for catchment areas less than 50km <sup>2</sup> . It does not consider spatial distribution of rainfall within a catchment area, which may lead to errors. It does not consider factors like antecedent moisture content, infiltration, evapotranspiration.	Rainfall intensity, time of concentration, area of catchment, coefficient of catchment.
SCS-CN method (Fantina, 2012)	It is very easy and simple to use considering only few factors like soil type, type of vegetation cover, land use, antecedent moisture condition and climate.	Knowledge and experience are required to find out the only one parameter CN. It does not realistically model the runoff when CN values are very low.	Curve number of the catchment area
Unit hydrograph method (US, 1973)	It is the simplest and most powerful tool in hydrology applicable for moderate size catchment area up to 5000 km <sup>2</sup> .	It is difficult to have a uniform rainfall excess distribution in space and time over the entire basin over the unit duration. It cannot be used for irregular shaped basins (long and narrow) which often has uneven rainfall distribution.	

### 6.3. Evapotranspiration equations

To calculate evapotranspiration from a catchment region, various formulas have been devised starting in 1965 with the Penman Monteith equation. The advantages, drawbacks,

requirements of the various methods have been compared. The results are shown in the Table 5 below (Subedl & Chavez, 2015).

Table 5: Different methods to estimate evapotranspiration from a catchment area.

<b>Method</b>	<b>advantages</b>	<b>limitations</b>	<b>variables used</b>
Penman-Monteith (1965)	Equation is considering $r_s$ and hence is more realistic in estimating ET	Since the equation includes $r_s$ , it is very difficult to obtain. Problems of	Net radiation, soil heat flux density, air density, specific heat of dry air, saturation vapour pressure, actual vapour pressure, psychrometric constant, canopy surface resistance, bulk surface aerodynamic resistance
FAO 56 PM Equation (1998)	Very accurate in calculating reference $E_t$ on daily basis	It might not be suitable for hourly timestep	Net radiation, soil heat flux density, mean daily air temperature, wind speed, saturation vapour pressure, actual vapour pressure, rate of change of saturation specific humidity with air temperature, psychrometric constant
Thornthwaite method (1948)	It is very simple to use and gives acceptable results	Problems of under estimation during winter and pre monsoon months	Mean daily temperature
Hargreaves method (1985)	It is simple and easy to use. Requires only basic factors.	Problems of over and at lower elevation sites and underestimation at higher elevation sites	Maximum minimum and average daily temperature
Priestly Taylor method (1972)	Relatively simple compared to PM method and uses only basic factors.	Cannot be used in regions with extreme climate conditions	Net radiation, soil heat flux density, psychrometric constant
Blaney Criddle method (1942)	Simple to use	It cannot be used where accurate data is needed due to overestimation	Mean daily percentage of annual daytime hours, average daily temperature
Lysimeter method	gives exact measurement	The setup is difficult to build up.	Precipitation, drainage, runoff, soil water storage
Water balance method	It is simple and reliable	If accurate data are not available, results have to be compromised	Precipitation, runoff, soil water storage

Hargreaves equation (1985) for estimating evapotranspiration has been adopted in the excel calculation model based on the comparative study due to its simplicity, necessity for fewer requirements and accuracy. Also, studies have proven that the results obtained from Hargreaves equation are found to be almost matching with the FAO Penman Monteith equation which is accepted as the most reliable and robust method to find out reference evapotranspiration (Hargreaves & Allen, 2003). The same equation used for calculating the evapotranspiration from a catchment area is applied for the purple green roofs of the green buildings.

#### 6.4. Infiltration equations.

To calculate the change in storage (infiltration) in a catchment area, different equations are there. The Table 6 below shows the advantages, limitations and variables required for the estimation of infiltration.

Table 6: Different methods to estimate infiltration from a catchment area.

<b>Method</b>	<b>advantages</b>	<b>limitations</b>	<b>requirements</b>
Horton infiltration method (S.C. Verma, 1982)	Since it has only few parameters, it is simple and easy to use.	Method is not accurate for long rainfall events. It assumes constant infiltration rate throughout the event, which is not true.	Final and initial infiltration rate. Decay constant, time, rainfall intensity.
$\phi$ index method (Sraj, Dirnbek, & Brilly, 2010)	It is suitable for wide range of soils. Provides quantitative measure of infiltration.	Method is limited to small areas.	Time, rainfall volume, runoff depth, area of catchment.
Philip method (J.S.C. Mbagwu, 1994)	Simple and easy to use. It can be used to estimate the future water storing ability of the soil, for future needs.	Considers only the soil characteristics, the vegetation and land cover are not considered.	Soil suction head hydraulic conductivity of soil from beginning of rainfall.
Green Amt method (Chen, Mao, & Wang, 2019)	Simple to use. Provides quantitative measure of infiltration.	It cannot be used in areas of high degree surface sealing.	Substrate depth field capacity and permanent wilting point of the soil.

Based on the comparative study made, Green amt method can be chosen for finding out the retention capacity of the green roofs of the buildings, with fewer requirements like field capacity, permanent wilting point of the soil and substrate depth. But for the calculation model, the retention capacity value of the green roof was taken directly from its manufacturers, the Sempergreen.

### **6.5. Volume of rainwater harvesting tank**

The research tries to understand how well stormwater runoff can be saved with the help of green building components at the time of precipitation and used within the property itself during a drought, so that a proper water balance between drought and precipitation events can be achieved. External water sources are not required because the stored water can be utilised in times of drought and there is no overflow flow from the property during normal-heavy precipitation events. As much as possible, the external inflow and outflow into and from the property are minimized, maintaining a balance between the volume of water accumulated and consumed with the use of green building components.

For that a rainwater harvesting tank was suggested and its volume was determined based on the runoff from the whole green building taken into consideration. Runoff from the whole Schauenstein Elementary school was taken as the sum of the runoff from the three building properties (sealed and green roof). The Excel calculation model that also aids in determining the size of a rainwater collecting tank within the green building premises is shown in the Figure 17 below. The Schauenstein School's buildings 1 and 2 (sealed areas) have a combined size of 1220 m<sup>2</sup>. Moreover, the runoff coefficient from purple roofs was assumed to be 40% rather than the 90% applied for normal roofs (Kim Y. , Kim, Park, & Han, 2014) (Mentens, Raes, & Hermy, 2006). In times of severe drought, it was also anticipated that water from the tank would be used to satisfy the water needs of the green space in front of the school as well as the purple roof.

Both the values of rainwater yield and water demand were compared. According to British standard Rainwater harvesting system code of practice BS 8515:2009, to calculate the volume of a rainwater harvesting tank, 5% of minimum of water yield and water demand should be considered. The model suggests that the tank should have a volume of 5% of water yield (which is the lesser value) approximately 59 m<sup>3</sup>, which is rounded to 70 m<sup>3</sup>.

<b>Volume of rainwater harvesting tank according to BS 8515:2009</b>		
	Total area of normal pitched roof (sqm)	1220
	Total area of green roof area (sqm)	640
	Annual average precipitation in catchment area (mm/year)	928
	runoff coefficient fro normal pitched roof	0,9
	runoff coefficient for extensive purple green roof	0,4
	filter effiecieny	0,95
	Runoff from pitched roof (l/year)	967996,8
	Runoff from green roof (l/year)	225689,6
<b>1.</b>	<b>Rainwater yield from all the roofs</b>	<b>1193686,4</b>
	Daily Water demand for irrigation in L/m2 in a year	200
	Green space area of school (front area) m2 approximate value	500
	water demand for green space in litres	36500000
	water demand for purple roof during extreme drought conditions (l)	21120
<b>2.</b>	<b>Total water demand for green space and purple roof</b>	<b>36521120</b>
	minimum value of 1 and 2	1193686,4
	5% of minimum of rainwater yield and water demand (litres)	59684,32
	Total volume of stormwater collection tank (l/year)	59684,32
	Total volume of stormwater collection tank (m3/year)	59,68

Figure 17: Calculation model to find out the volume of rainwater harvesting tank - Schauenstein (own creation).

## 6.6. Calculation of runoff from extreme and normal precipitation event

The mathematical model indicates that the 5% of rainwater yield = 59m<sup>3</sup> has a lower value. Hence, a 70 m<sup>3</sup> rainwater collection tank was recommended. The calculation model also had been used to check whether the tank was sufficient to meet the runoff from the Schauenstein Elementary school during the times of extreme and normal weather events. The Figure 18 below depicts the runoff in Schauenstein during the storm event on July 13, 2021. Additionally, the runoff for a regular precipitation event is also shown in the Figure 18 below. The same calculation table can be used to determine the runoff from a specific event and to determine whether the designed volume of a rainwater harvesting tank was adequate for a specific storm event.

The findings indicate that the tank's volume was enough for typical precipitation events. However, during periods of intense rain, such as the one on July 13, 2021, the amount of runoff was significantly greater than the capacity of the tank. As a result, such a storm event may cause an overflow, which requires alternate safeguards or preparations.

Condition	1. Extreme Precipitation	2. Normal Precipitation
Date	13/07/2021	17/09/2011
Precipitation value in mm	90	40,00
Precipitation value in mm just before the drought event	NA	NA
maximum temperature	26,4	21,5
minimum temperature	12,9	11,5
average temperature	19,65	16,5
Annual average precipitation in catchment area (mm/year)	928	928
latitude of location in radians	0,875457153	0,875457153
Julian day	194	260
Solar declination	0,380	0,023
Sunset hour angle	2,070	1,598
Inverse relative distance earth-sun	0,968	0,992
Extra terrestrial radiation	11,084	0,391
ET using hargreaves eqn (mm/day)	3,36	0,09
Crop coefficient	0,56	0,56
plant stress coefficient	1	0,7
Actual evapotranspiration (mm/day)	1,88	0,04
When rainfall reaches maximum value, cumulative rainfall volume is around 64% in Euler 2	57,6	25,6
maximum retention mm (from manufacturers)	33	33
Maximum detention mm (from manufacturers)	57,41	57,41
Area of the green roof (m2)	640	640
Input precipitation received by the roof (l/day)	57600,0	25600,0
Actual evapotranspiration from the roof (l/day)	1202,5	23,4
Storage with retention (l)	21120,0	21120,0
Storage with retention (l) - assuming due to prior rain event only 50% retention volume is possible	10560,0	10560,0
Storage with detention (l)	36742,4	36742,4
Percentage of detention storage filled with water after completely filling the retention storage	0,72	0,16
Amount of water stored inside the detention storage	26304,0	5824,0
Runoff from the roof (l/day)	19533,5	9192,6
Runoff from the roof (mm/day)	31	14
Area of building 1	745	745
Area of building 2	475	475
runoff coefficient of normal pitched roofs	0,9	0,9
Rainfall received in building 1 roof (l/day)	60345,00	26820,00
Rainfall received in building 2 roof (l/day)	38475,00	17100,00
Volume of rainwater harvesting tank needed (litres/day)	118353,5	53112,6
Volume of rainwater harvesting tank needed in m3/day	118,35	53,11
Result	<b>Overflow</b>	<b>Safe</b>

Figure 18: Calculation of runoff from storm event- Schauenstein (own creation)

The detention modeller developed by Green Roof Diagnostics was used to verify the results and determine whether the calculation model was reliable. It was discovered that the outcomes were comparable. Slight variations were seen with the results, it might be because the detention modeller software did not consider evapotranspiration, assuming that at the time of heavy rainfall the effects of evapotranspiration were negligible compared to the input rainfall and hence could be neglected. According to the detention modeler's predictions, an overflow of around 31 mm will occur for a storm event of 85 mm (as on July 13, 2021) over the course of 24 hours, which fills the retention storage of the purple roof by 100% and detention storage by 65%, same as calculated by the excel sheet. The Figures 19 and 20 below displays the outcome of the green roof diagnostics using the detention modeller software.

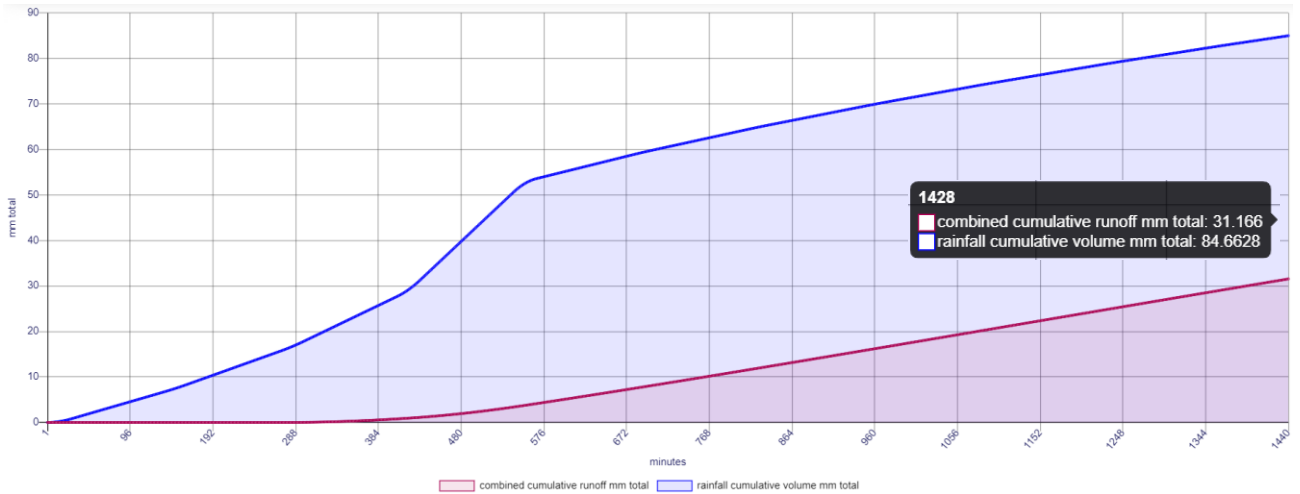


Figure 19: Results from detention modeller for a rainfall event of 85mm lasting for 24 hours (taken from detention modeller software of green roof diagnostics-currently not opened for public to access).

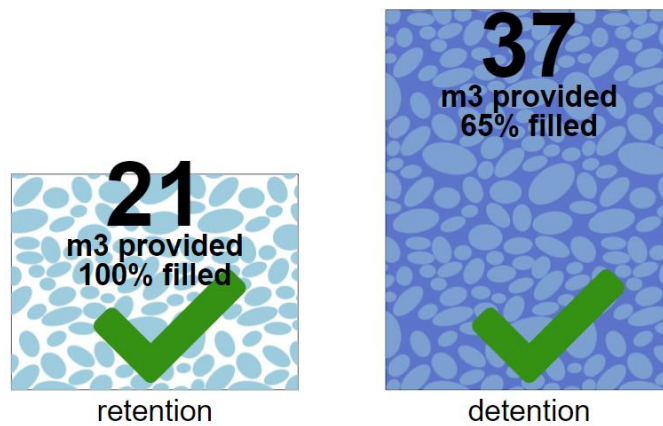


Figure 20: Results from the detention modeller showing percentage of retention and detention storage fulfilment for the event on 13.07.2021 (taken from detention modeller software of green roof diagnostics-currently not opened for public to access).

## 6.7. Tank for extreme drought events

The model was also used to determine whether the rainfall in the tank is enough to satisfy the roof's water needs or whether other water input sources are required. As an illustration, a three week long drought occurred in July 1976 was taken into consideration. The calculating model predicted that the runoff from the purple roof due to the rainfall prior to the drought event, will be negligible and that it will be around 11m<sup>3</sup> from the Schauenstein school's normal pitched roofs (from the sealed area).

The manufacturers of purple roof, Sempergreen, advises to provide the water equal to the retention capacity of the roof only during the periods of severe drought, lasting longer than two weeks. The mathematical model is depicted in the Figure 21 below along with data



values from a drought event in July 1976. The discharge from the school's regular pitched roofs was about 11m<sup>3</sup>, which is not enough to meet the purple roof's water needs (retention capacity of the green roof in Schauenstein Elementary school = 21m<sup>3</sup>). As a result, the rainwater collection tank's water supply is not sufficient to meet the water needs of the purple roof and additional external sources are required. Hence the study suggests making use of water from the nearby slopy ground as shown in Figure 15 above. The Figure 21 below shows the calculation model with the drought event in 1976 to find out the volume of water inside the rainwater harvesting tank during the drought event.

Condition	Drought event extended for more than 2 weeks
Date	01/07/1976
Precipitation value in mm	0
Precipitation value in mm just before the drought event (mm)	9,8
maximum temperature	26,7
minimum temperature	12,8
average temperature	19,75
Annual average precipitation in catchment area (mm/year)	928
latitude of location in radians	0,875457153
Julian day	183
Solar declination	0,402
Sunset hour angle	2,105
Inverse relative distance earth-sun	0,967
Extra terrestrial radiation	12,056
ET using hargreaves eqn (mm/day)	3,71
Crop coefficient	0,58
plant stress coefficient	0,1
Actual evapotranspiration(mm/day)	0,21
When rainfall reaches maximum value, cumulative rainfall volume is around 64% in Euler 2	6,272
maximum retention mm (from manufacturers)	33
Maximum detention mm (from manufacturers)	57
Area of the roof (m <sup>2</sup> )	640
Input precipitation received by the roof(l/day)	6272,0
Actual evapotranspiration from the roof(l/day)	133,1
Storage with retention(l)	2120,0
Storage with retention(l) - assuming due to prior rain event only 50% retention volume is possible	10560,0
Storage with detention(l)	36480,0
Percentage of detention storage filled with water after completely filling the retention storage capacity	0,0
Amount of water stored inside the detention storage	0,0
Runoff from the roof(l/day)	0,0
Runoff from the roof(mm/day)	0,0
Area of building 1& 2	1220
Rainfall received in building 1& 2 roof due to the rainfall prior to the drought event(l/day)	10760,4
Volume of water coming to the tank due to the rainfall prior to the drought event (litres/day)	10760,4
Volume of water inside the tank due to the rainfall prior to the drought event(l/day in m <sup>3</sup> /day)	10,76
water demand of the purple roof in litres	21120
Does it needs external water sources	yes

Figure 21: Calculation model to check whether the water demands of the purple roof can be met using rainwater harvesting tank- Schauenstein (own creation).

## 6.8. Tank for 3a, 5a,10a and 100a storm events

Using KOSTRA-DWD data for the Schauenstein region, the utility of the rainwater harvesting tank for designing storm events in the future was also assessed. The volume of the tank was monitored for the precipitation events over a period of 24 hours with return periods of 3, 5, 10 and 100 years. In the Schauenstein region, it is recommended that a storm event's precipitation value be 51.6, 58.7, 69 and 108.5 mm for a 24-hour period with a return

period of 3, 5, 10 years and 100 years respectively (refer figure 4). To test whether the rainwater collection tank was sufficient, the calculating model used the precipitation values from these four events. The volume of water that entered the rainwater collection tank during these four storm occurrences is depicted in the Figure 22 below.

Return period	3a	5a	10a	100a
Date	01/07/2025	01/07/2025	01/07/2025	01/07/2025
Precipitation value in mm	51,6	58,7	69,00	108,5
Precipitation value in mm just before the drought event	NA	NA	NA	NA
maximum temperature	26,4	26,4	26,4	26,4
minimum temperature	12,9	12,9	12,9	12,9
average temperature	19,65	19,65	19,65	19,65
Annual average precipitation in catchment area (mm/year)	928	928	928	928
latitude of location in radians	0,875457153	0,875457153	0,875457153	0,875457153
Julian day	182	182	182	182
Solar declination	0,403	0,403	0,403	0,403
Sunset hour angle	2,107	2,107	2,107	2,107
Inverse relative distance earth-sun	0,967	0,967	0,967	0,967
Extra terrestrial radiation	12,115	12,115	12,115	12,115
ET using hargreaves eqn (mm/day)	3,67	3,67	3,67	3,67
Crop coefficient	0,56	0,56	0,56	0,56
plant stress coefficient	1	1	1	1
Actual evapotranspiration(mm/day)	2,05	2,05	2,05	2,05
When rainfall reaches maximum value, cumulative rainfall volume is around 64% in Euler 2	33,024	37,568	44,16	69,44
maximum retention mm (from manufacturers)	33	33	33	33
Maximum detention mm (from manufacturers)	57,84	57,41	57,41	57,41
Area of the roof (m <sup>2</sup> )	640	640	640	640
Input precipitation received by the roof(l/day)	33024,0	37568,0	44160,0	63440,0
Actual evapotranspiration from the roof(l/day)	1314,4	1314,4	1314,4	1314,4
Storage with retention(l)	21120,0	21120,0	21120,0	21120,0
Actual Storage with retention(l)- assuming 50% AMC	10560	10560	10560	10560
Storage with detention(l)	37017,6	36742,4	36742,4	36742,4
Percentage of detention storage filled with water after completely filling the retention storage	0,29	0,37	0,48	0,92
Amount of water stored inside the detention storage	10575,4	13483,5	17702,4	33881,6
Runoff from the roof(l/day)	10574,2	12210,1	14583,2	23684,0
Runoff from the roof(mm/day)	17	19	23	37
Area of building 1	745	745	745	745
Area of building 2	475	475	475	475
Runoff coefficient for normal roofs	0,9	0,9	0,9	0,9
Rainfall received in building 1 roof(l/day)	34597,80	39358,35	46264,50	72749,25
Rainfall received in building 2 roof(l/day)	22059,00	25094,25	29497,50	46383,75
Volume of runoff into the harvesting tank (litres/day)	67231,0	76662,7	90345,2	142817,0
Volume of rainwater harvesting tank needed in m <sup>3</sup> /day	67,23	76,66	90,35	142,82
Result	safe	overflow	overflow	overflow

Figure 22: Calculation model to check the functionality of rainwater harvesting tank for 3a, 5a, 10a and 100a storm events- Schauenstein (own creation).

The findings showed that the 70 m<sup>3</sup> rainwater harvesting tank that was suggested was acceptable for storm events with a return period of three years, but not for the events with a return period of 5, 10 and 100 years. However, the volume of runoff water into the tank was approximately 76,90 and 142 m<sup>3</sup> for storm events with a return duration of 5, 10 and 100 years respectively for a duration of 24 hours, for which the tank is insufficient and may result in an overflow from the rainwater harvesting tank. Due to the possibility of an overflow caused by such a storm occurrence, a larger tank of higher capacity around 140 m<sup>3</sup> was suggested, based on the results from the runoff from a 100-year event for the area. It is better to provide two tanks of volume 70m<sup>3</sup> each so that when one tank is under maintenance, water can be stored in the other tank.

## 6.9. Calculation model on Hochschule Campus

Runoff from the whole Hochschule campus was taken as the sum of the runoff from the buildings A, B, C, D, E, G, Einstein building and mobile units (refer figure 5). Using the calculation model, the runoff from extreme and normal precipitation events were calculated and checked whether the retention pond in the front area had sufficient capacity to store the runoff water. The Figure 23 below depicts the runoff from the campus buildings during the storm events on 13.07.2021 and 17.09.2021. The findings indicate that the retention pond was enough even for extreme events as the one on July 2021. Hence there is no need to have any external sources to collect run off water from the future green building university campus.

Condition	Extreme precipitation	Normal precipitation
Date	13/07/2021	17/09/2021
Precipitation value in mm	85	40
Maximum Temperature	26.4	26.4
Minimum Temperature	12.9	12.9
Average Temperature	19.65	19.65
Latitude of location in radians	0.878110053	0.878110053
Julian Date	194	260
Solar declination	0.38	0.02
Sunset hour angle	2.07	1.60
Inverse relative distance earth-sun	0.97	0.99
Extra terrestrial radiation	11.14	0.39
ET using Hargraeves eqn (mm/day)	3.37	0.12
Crop coefficient	0.56	0.56
Plant stress coefficient	1	1
Actual evapotranspiration (mm/day)	1.89	0.07
When rainfall reaches maximum value, cumulative rainfall volume around 60%	51	24
maximum retention (mm) (from manufacturers)	33	33
Maximum detention (mm) (from manufacturers)	57.41	57.41
Area of the building A+B+C+E+ mobile units+G+ Einstein building(m <sup>2</sup> )	14548	14548
Area of Building D (m <sup>2</sup> )	752	752
Storage with retention(l) - assuming due to prior rain event only 50% retention volu	16.5	16.5
Storage with detention(l)	57.4	57.4
Percentage of detention storage filled with water	0.60	0.13
Amount of water stored inside the detention storage	34.5	7.5
Total runoff from the green roofs(mm/day)	32	16
Total runoff from the green roof buildings (l/day)	467160.88	231800.34
Runoff coefficient from building D	0.9	0.9
Runoff from normal pitched roof building D (l/day)	57528.00	27072.00
Total runoff from all the buildings A+B+C+D+E+G+ Einstein building+mobile uni	524688.9	258872.3
Total runoff from all the buildings A+B+C+D+E+G+ Einstein building+mobile uni	524.7	258.9
Volume of retention pond in m <sup>3</sup>	1200	1200
Result	Safe	Safe

Figure 23: Calculation model to compute runoff for a particular storm event in Hochschule (own creation).

The model was also utilized to figure out whether the retention pond's runoff water was sufficient to meet the roof's water needs or whether other water input sources were necessary. As an illustration, the same drought event occurred in July 1976 was considered. The calculating model forecasted that the purple roof's runoff will be insignificant, which is

insufficient to supply the water requirements of all the purple roofs of the future green campus. In times of drought, the water demand for the entire green roof area is around 480m<sup>3</sup>, which is far more than the amount of water in the pond, necessitating the use of extra external sources. The water requirement for the green roof and runoff during the drought episode is shown in the Figure 24 below.

Condition	Drought event extended for more than 2 weeks
Date	01/07/1978
Precipitation value in mm	0
Precipitation value in mm just before the drought event (mm)	9.8
maximum temperature	26.7
minimum temperature	12.8
average temperature	19.75
Annual average precipitation in catchment area (mm/year)	928
latitude of location in radians	0,87810053
Julian day	183
Solar declination	0,402
Sunset hour angle	2,108
Inverse relative distance earth-sun	0,967
Extra terrestrial radiation	12,118
ET using hargreaves eqn (mm/day)	3,73
Crop coefficient	0,56
plant stress coefficient	0,1
Actual evapotranspiration(mm/day)	0,21
When rainfall reaches maximum value, cumulative rainfall volume is around 64% in Euler 2	6,272
maximum retention mm (from manufacturers)	33
Maximum detention mm (from manufacturers)	57
Area of Building D (m <sup>2</sup> )	752
Total area of buildings with green roofs A+B+C+E+G+ Einstein building+mobile units	14548
Input precipitation received by the green roofs(l/day)	142570,4
Actual evapotranspiration from the roof(l/day)	3040,8
Storage with retention(l) – assuming due to prior rain event inly 50% retention volume is possible	240042,0
Storage with detention(l)	829236,0
Percentage of detention storage filled with water after completely filling the retention storage	0,0
Amount of water stored inside the detention storage	0,0
Runoff coefficient of green roofs	1,0
Runoff from the green roofs(l/day)	0,0
Runoff coefficient of normal roofs	0,9
Rainfall received in normal pitched roof building D due to the rainfall prior to the drought event(l/day)	6632,64
Volume of water coming to the retention pond due to the rainfall prior to the drought event (litres/day)	6632,6
Volume of water inside the pond due to the rainfall prior to the drought event in m <sup>3</sup> /day	6,63
water demand of the purple roof in litres	480084,0
Does it needs external water sources	yes

Figure 24: Calculation model to find the water demands of the purple roof in Hochschule campus during a drought event (own creation).

The usefulness of the retention pond for storm events in the future was also evaluated using KOSTRA-DWD data for the Hof region. With return periods of 3, 5, 10, and 100 years, the volume of the pond was tracked for the precipitation events over a period of 24 hours. The proposed storm event precipitation values for the Hof region are 48.3, 55, 64.7, and 102 mm over a 24-hour period, with return periods of 3, 5, 10 and 100 years, respectively (refer figure 6). The calculating model used the precipitation values from these four events to determine whether the retention pond was sufficient to meet the runoff from the campus roofs. Figure 25 below shows the calculation of the runoff for these four events. The results demonstrated

that the retention pond's capacity was suitable for storm occurrences with return intervals of 3, 5, 10, and 100 years. However, the pond is enough for storm events with a return period of 100 years and a duration of 24 hours because the amount of runoff water into the pond is about 630 m<sup>3</sup> which is less compared to the volume of the pond.

Return period	3a	5a	10a	100a
Date	13/07/2021	14/07/2021	15/07/2021	16/07/2021
Precipitation value in mm	48,3	55	64,70	102,00
Maximum Temperature	26,4	26,4	26,4	26,4
Minimum Temperature	12,9	12,9	12,9	12,9
Average Temperature	19,65	19,65	19,65	19,65
Latitude of location in radians	0,8781101	0,878110053	0,878110053	0,878110053
Julian Date	194	195	196	197
Solar declination	0,38	0,38	0,37	0,37
Sunset hour angle	2,07	2,07	2,06	2,06
Inverse relative distance earth-sun	0,97	0,97	0,97	0,97
Extra terrestrial radiation	11,14	11,02	10,90	10,78
ET using Hargraeves eqn (mm/day)	3,37	3,34	3,30	3,26
Crop coefficient	0,56	0,56	0,56	0,56
Plant stress coefficient	1	1	1	1
Actual evapotranspiration mm/day)	1,89	1,87	1,85	1,83
When rainfall reaches maximum value, cumulative rainfall volume is around 60	28,98	33	38,82	61,2
maximum retention mm( from manufacturers)	33	33	33	33
Maximum detention mm (from manufacturers)	57,41	57,41	57,41	57,41
Area of the building A+B+C+E+G+mobile units+Einstein building (m <sup>2</sup> )	14548	14548	14548	14548
Area of Building D (m <sup>2</sup> )	752	752	752	752
Storage with retention(l) - assuming due to prior rain event only 50% retention vol	16,5	16,5	16,5	16,5
Storage with detention(l)	57,4	57,4	57,4	57,4
Percentage of detention storage filled with water after completely filling the reten	0,22	0,29	0,39	0,78
Amount of water stored inside the detention storage	12,5	16,5	22,3	44,7
Total runoff from the green roofs(mm/day)	17	20	24	39
Total runoff f from the green roof buildings A+B+C+E+mobile units (l/day)	253596,24	292872,20	349615,96	566979,55
Runoff coefficient from building D	0,9	0,9	0,9	0,9
Runoff from normal pitched roof building D (l/day)	32689,44	37224,00	43788,96	69033,60
Total runoff from all the buildings A+B+C+D+E+mobile units (l/day)	286285,7	330096,2	393404,9	636013,1
Total runoff from all the buildings A+B+C+D+E+mobile units (m <sup>3</sup> /day)	286,3	330,1	393,4	636,0
Volume of retention pond in m <sup>3</sup>	1200	1200	1200	1200
Result	Safe	Safe	Safe	Safe

Figure 25 : Calculation model to check the functionality of retention pond for 3a, 5a, 10a and 100a storm events in Hochschule Hof (own creation).

## 6.10. Importance of water balance model and its components

Conducting a water balance model study on a building or property can determine if a stormwater management technique is necessary or not. If so, the water balance method can also be used to identify the required capacity of the technique. Additionally, the water balance model study of a property can assesses if there is an excessive human intervention in the catchment area. A proper balance in the hydrological cycle is essential to be maintained. Adequate storage and evapotranspiration should be ensured to control runoff, especially in urban areas where runoff can be difficult to manage. If the components such as evapotranspiration and storage are insufficient in a building/ property, they can be improved by implementing appropriate stormwater techniques such as green roofs, rainwater tanks

and green spaces. This decentralized approach can effectively reduce runoff. While comparing the effects of both storage (retention and detention) and evapotranspiration on runoff from a building and its surrounding premises, the component storage is found to have more effect on surface runoff than evapotranspiration. For example, from the figure 26 below, the evapotranspiration rate from the roof is  $1.89 \text{ mm/m}^2$  whereas storage rate is around  $90 \text{ mm/m}^2$ .

Moreover, a water balance model can identify the potential runoff from a catchment during a specific storm event. This allows for necessary precautions to be taken before the event, such as emptying the rainwater harvesting tank, which can reduce the likelihood of sewer overflow or pressure on treatment plants on a small scale. In the research study, the tank capacity was assessed for future events with a return period of 3, 5, 10 and 100 years using a water balance calculation model. It was discovered that overflow may occur for events with a 5-year return period, indicating the need for higher volume tanks. Also, the same technique has been used to identify whether the water demands of the green roof at drought period can be solved using water from the rainwater harvesting tank. In whole the water balance modelling considering the water accumulation and consumption of the building and its nearby properties, helps to achieve proper water management between drought and precipitation events in a decentralised manner. Hence, this study highlights the importance of applying a water balance model in a green building and its surrounding premises.

### **6.11. Importance of green buildings and stormwater management techniques**

To identify the importance of green buildings in stormwater management, a study was done in Hochschule campus by calculating runoff from the campus for the storm event on 13.7.2021 with and without green roofs. The model results showed that the runoff can be reduced to about half with the aid of green building components. The total runoff from the campus buildings were around  $525 \text{ m}^3$  with the help of green roofs and around  $1170 \text{ m}^3$  without purple green roofs. The findings are shown in Figure 26 below.

According to the findings of the research study, the significance of green buildings and stormwater management methods has been clearly established. In areas where moderate to heavy rainfall occurs annually, the implementation of effective water management techniques can help to utilize excess runoff water. In the past, this runoff water from rooftops would have been channelled into sewer systems and eventually treated at wastewater

treatment plants, which can put pressure on the system during heavy rainfall. However, with proper stormwater management techniques such as green roofs and rainwater harvesting tanks, the runoff water can be stored and used during drier periods, eventually returning to the atmosphere as vapor, thereby balancing the water cycle.

Condition	With green roof	Without green roof
Date	13/07/2021	13/07/2021
Precipitation value in mm	85	85
Maximum Temperature	26,4	26,4
Minimum Temperature	12,9	12,9
Average Temperature	19,65	19,65
Latitude of location in radians	0,878110053	0,878110053
Julian Date	194	194
Solar declination	0,38	0,00
Sunset hour angle	2,07	0,00
Inverse relative distance earth-sun	0,97	0,00
Extra terrestrial radiation	11,14	0,00
ET using Hargraeves eqn (mm/day)	3,37	0,00
Crop coefficeint	0,56	0
Plant stress coefficient	1	0
Actual evapotranspiration mm/day)	1,89	0,00
When rainfall reaches maximum value, cumulative rainfall volume is around 60%	51	0
maximum retention mm( from manufacturers)	33	0
Maximum detention mm (from manufacturers)	57,41	0
Area of the building A+B+C+E+G+mobile units+Einstein building (m2)	14548	14548
Area of Building D (m2)	752	752
Storage with retention(I) - assuming due to prior rain event only 50% retention volume	16,5	0,0
Storage with detention(I)	57,4	0,0
Percentage of detention storage filled with water after completely filling the retention storage	0,60	0,00
Amount of water stored inside the detention storage	34,5	0,0
Total runoff from the green roofs(mm/day)	32	0
Total runoff f from the bildings A+B+C+E+G+ Einstein building+mobile units (l/day)	467160,88	1112922,00
Runoff coefficient from building D	0,9	0,9
Runoff from normal piteched roof building D (l/day)	57528,00	57528,00
Total runoff from all the buildings A+B+C+D+E+G+ Einstein building+mobile units (l/day)	524688,9	1170450,0
Total runoff from all the buildings A+B+C+D+E+G+ Einstein building+mobile units (m3/day)	524,7	1170,5

*Figure 26: Calculation model to compare the runoff with and without green roof in Hochschule Campus (own creation).*

## **7. Conclusion and recommendations**

### **7.1. Conclusion**

Urban areas are more vulnerable to frequent extreme events like floods and droughts due to its sealed surfaces and limited permeable spaces. One of the major stormwater management strategy- the green buildings and its importance are studied in this research. The study explored the potential of green buildings to manage stormwater in two small-sized catchment areas. The research analysed the selected buildings and their surrounding properties, the various components of their water balance involved, the methods to calculate them, its advantages, limitations, and requirements were also compared. Based on the study, an excel-based calculation model has been developed focusing on the stormwater management aspect, to find out the major components involved in the water balance of the green building and its surrounding properties that can influence the surface runoff from the property. The developed calculation model works on the major aspects of water accumulation and consumption of selected green buildings and its surroundings. The tool can be used to predict runoff from the properties during different storm events, based on which the volume of a stormwater collection tank can be calculated, which can store runoff from the catchment area and can be used during droughts for irrigation purposes, thereby reducing the pressure on drainage flow and water treatment plants. The study also tries to identify the effects of water balance parameters like rainfall, evapotranspiration and storage on runoff from a property. The model also checks the tank's condition for future storm using KOSTRA DATA 2020.

The prediction model enables the estimation of runoffs from storm events in advance, allowing the tank to be emptied before the event and made ready for upcoming events. Overall, the findings of the study suggest that green buildings, in conjunction with appropriate stormwater management measures, can effectively mitigate the impact of stormwater on the areas. The study provides valuable insights for planners and policy makers to develop sustainable solutions for stormwater management in small-sized catchment areas. In addition to retention ponds and rainwater harvesting tanks, the study also suggests the use of purple roofs in the catchment areas. Purple roofs offer both detention and retention properties, effectively reducing surface runoff and delaying the time of runoff by 8-24 hours (Detention roof, 2023). This makes them an effective solution for reducing runoff within the property itself. In case of heavy storm events that exceed the capacity of green roofs, the runoff can be stored in the rainwater harvesting tank or retention ponds until the precipitation



subsidies. This approach reduces the pressure on drainage systems and water treatment plants during heavy storms.

Overall, the study recommends the use of a combination of different green building components like purple roofs and rainwater harvesting tanks or retention ponds to manage stormwater in small-sized catchment areas effectively. While the studies and suggestions in this research pertain to a smaller area, it is important to note that their impact may be limited compared to the entire city. However, if similar strategies and approaches are implemented on a small scale for every building and property, the cumulative impact could be significant. As extreme weather events become more frequent in the future, it is crucial to introduce better stormwater management strategies for more building/properties. Governments can incentivize the adoption of these strategies to make them more widely accepted. To create a culture of sustainability and awareness around the topic of stormwater management and green buildings, it is recommended that the topic be introduced in school lectures. This will help raise awareness among young people and encourage them to make informed choices about their future homes and workplaces. Ultimately, a collective effort is needed to achieve more sustainable stormwater management practices across urban areas.

## **7.2. Limits**

The major limitation of the research study was the lack of availability of data from external experts, which might have affected the results of the calculation model. The accuracy of the results of the excel calculation sheet could have been improved, if more information about the purple roof profile could have been obtained. The data presented in this thesis is limited to the available sources and might have affected the reliability and accuracy of the results. Although maximum efforts were made to minimise the impact of the limitations as much as possible, results of the calculation sheet should be taken only after detailed analysis. Future research in this field could be made more accurate and reliable by overcoming this limitation, by adding more data from expert sources in the field of green roofs and buildings.

## **7.3. Recommendations**

Based on the previous discussion, conclusions and limits, few recommendations are made for improving the quality of the future study related to these topics:

1. Crop coefficients and water stress coefficients play a crucial role in controlling evapotranspiration and these coefficients vary depending on soil and weather conditions. However, for the calculation model's development, specific values were

selected based on literature research, which may result in slight discrepancies compared to actual conditions. Therefore, it is recommended to consider more accurate and precise values that better reflect real conditions.

2. The Hargreaves equation 1985 was used in the model to determine evapotranspiration due to a lack of data availability in the investigation area. However, studies have demonstrated that the Penman-Monteith equation produces more accurate results that align with real-time data compared to other methods. Hence, if sufficient data are accessible, it is recommended to determine evapotranspiration using the Penman-Monteith equation.
3. The calculation model prepared in excel might contain errors and cross checking can be done before using for future works.

#### **7.4. Future scope of study**

1. Expansion of the study area: The current study focuses on a small-sized catchment area, which includes a single building or property, but there is scope for expanding the study area to cover larger catchment areas. This would help in understanding the impact of stormwater management strategies on a larger scale.
2. Long-term digital conditioning monitoring and water distribution control concept: Long-term digital monitoring of the implemented stormwater management strategies could be conducted to evaluate their effectiveness in reducing runoff and improving water quality. This would help in identifying any potential issues or areas for improvement.
3. Development of decision support tools: The development of decision support tools, such as mobile applications or web-based platforms, could be considered to help property owners or managers in making informed decisions regarding stormwater management.
4. Community engagement: Community engagement and education programs could be developed to increase awareness and understanding of the benefits of sustainable stormwater management practices. This could include workshops, educational campaigns, and community-led initiatives.

## **Affidavit**

I certify that this thesis does not incorporate without acknowledgement any material previously submitted for a degree or diploma in any university; and that to the best of my knowledge and belief it does not contain any material previously published or written by another person where due reference is not made in the text.

Hof

Date:

Signature

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Jasmin Rose Mundackal

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