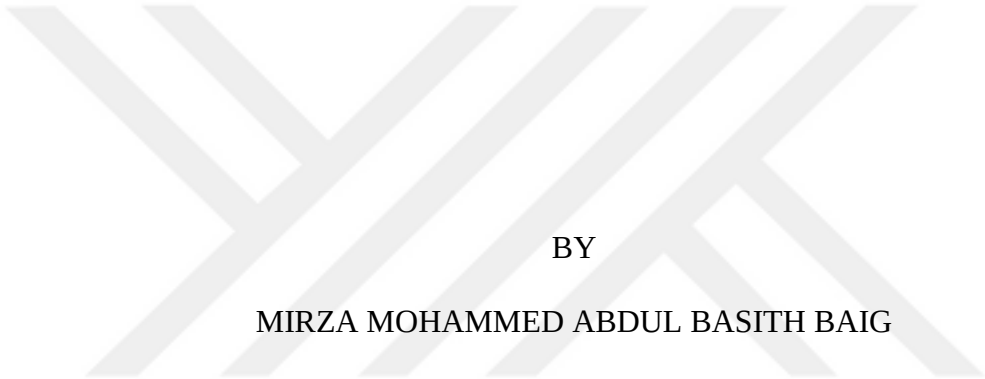


SUSTAINABLE STORMWATER MANAGEMENT: CASE STUDY FOR METU
NORTHERN CYPRUS CAMPUS AND THE TOWN OF GUZELYURT

A THESIS SUBMITTED TO
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BY

MIRZA MOHAMMED ABDUL BASITH BAIG

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Approval of the Board of Graduate Programs

Prof. Dr. Cumali Sabah

Chairperson

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science

Assoc. Prof. Dr. Ceren İnce Derogar

Program Coordinator

This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

Asst. Prof. Dr. Bertuğ Akintuğ

Supervisor

Examining Committee Members

Asst. Prof. Dr. Abdullah Ekinici
Civil Engineering METU NCC

Asst. Prof. Dr. Bertuğ Akintuğ
Civil Engineering METU NCC

Assoc. Prof. Dr. İme Akanyeti
Faculty of Engineering CIU



I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last name: Mirza Mohammed Abdul Basith, Baig

Signature:

ABSTRACT

SUSTAINABLE STORMWATER MANAGEMENT: CASE STUDY FOR METU NORTHERN CYPRUS CAMPUS AND THE TOWN OF GUZELYURT

Baig, Mirza Mohammed Abdul Basith
Master of Science, Sustainable Environment and Energy Systems Program
Supervisor: Asst. Prof. Dr. Bertuğ Akıntuğ

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This study addresses the challenges posed by rapid urbanization and climate change on traditional piped drainage systems, which often lead to pluvial flooding and associated damages. As an alternative, a sustainable urban drainage system incorporating low impact development (LID) practices is implemented at the Middle East Technical University, Northern Cyprus Campus. The LID practices include bio-retention basins, permeable pavements, and rainwater harvesting systems. The research findings demonstrate significant reductions in both runoff volume and peak discharge, with the maximum reductions observed at 96.42% and 92.85%, respectively. Moreover, a notable reduction of 65% in pollutants is achieved. Life cycle assessment (LCA) is conducted to evaluate the environmental costs associated with the LID practices. Results reveal that the rainwater harvesting system exhibits the lowest environmental impact, followed by the bio-retention system and permeable pavement system. Furthermore, the implementation of LID strategies in Guzelyurt Town demonstrates their efficacy in reducing runoff volume and peak discharges while enhancing the stormwater drainage system's capacity to handle rainfall intensities of up to 40 mm/hr. A comparative analysis is conducted between LID solutions and a traditional approach for flood mitigation in Guzelyurt,

with the LCA indicating that LID solutions have a higher environmental impact than the traditional method. Finally, an economic analysis reveals that implementing LID solutions in Guzelyurt catchment incurs approximately three times higher costs which was 4,712,104 TL (206,229 USD) compared to the traditional approach which was 1,683,208 TL (71,322 USD).

Keywords: Urban Flooding, Sustainable Stormwater Management, Life Cycle Assessment, SWMM, OpenLCA



ÖZ

SÜRDÜRÜLEBİLİR YAĞMUR SUYU YÖNETİMİ: ODTÜ KUZEY KIBRIS KAMPUSU VE GÜZELYURT KASABASI ÖRNEK İNCELEMESİ

Baig, Mirza Mohammed Abdul Basith
Yüksek Lisans, Sürdürülebilir Çevre ve Enerji Sistemleri Program
Tez Yöneticisi: Dr. Öğr. Üyesi Bertuğ Akıntuğ

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Bu çalışma, hızlı kentleşme ve iklim değişikliğinin geleneksel yağmursuyu drenaj sistemlerinde ortaya çıkardığı ve genellikle aşırı taşkınlara ve buna bağlı hasarlara yol açan zorlukları ele almaktadır. Alternatif olarak, Orta Doğu Teknik Üniversitesi Kuzey Kıbrıs Kampüsü'nde düşük etkili gelişme (LID) uygulamalarını içeren sürdürülebilir bir kentsel yağmursuyu drenaj sistemi uygulanmaktadır. LID uygulamaları biyolojik- tutma havzalarını, geçirgen kaldırımları ve yağmur suyu toplama sistemlerini içerir. Araştırma bulguları, sırasıyla %96,42 ve %92,85'te gözlenen maksimum azalmalarla, hem akış hacminde hem de en yüksek deşarj değerinde önemli azalmalar olduğunu göstermektedir. Ayrıca, kirleticilerde %65'lik kayda değer bir azalma sağlanmıştır. LID uygulamalarıyla ilişkili çevresel maliyetleri değerlendirmek için yaşam döngüsü değerlendirmesi (LCA) yapılır. Sonuçlar, yağmur suyu toplama sisteminin en düşük çevresel etkiyi sergilediğini, ardından biyolojik-tutma sistemi ve geçirgen kaplama sisteminin geldiğini ortaya koymaktadır. Ayrıca, Güzelyurt kasabasında LID stratejilerinin uygulanması, yağmur suyu drenaj sisteminin 40 mm/saat'e kadar olan yağış yoğunluklarıyla başa çıkma kapasitesini geliştirirken, akış hacmini ve pik deşarjları azaltmadaki etkinliğini göstermektedir. Güzelyurt'ta LID çözümleri ile geleneksel taşkın azaltma yaklaşımı arasında karşılaştırmalı bir analiz yapılmıştır ve LCA, LID

özümünün geleneksel yöntemden daha yüksek çevresel etkiye sahip olduğunu göstermektedir. Son olarak, ekonomik bir analiz, Güzelyurt kasabasında LID çözümlerinin uygulanmasının, 1.683.208 TL (71.322 USD) olan geleneksel yaklaşıma kıyasla yaklaşık üç kat daha fazla maliyete 4.712.104 TL (206.229 USD) neden olduğunu ortaya koymaktadır.

Anahtar Kelimeler: Kentsel Sel, Sürdürülebilir Yağmur Suyu Yönetimi, Yaşam döngüsü Değerlendirmesi, SWMM, OpenLCA



Dedicated to My Family

To my beloved mother, Mirza Naseem Unisa Irfana, my late father, Mirza Afsar Baig, and my two elder sisters, thank you for your unwavering love, support, and inspiration. Your presence in my life has been a driving force behind my achievements. I am forever grateful for your belief in me

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LIST OF ABBREVIATIONS

ABBREVIATIONS

LID	Low Impact Development
BRB	Bio-retention Basin
PPS	Permeable Pavement System
RWH	Rain water Harvesting
SSWMP	Sustainable Stormwater Management Practises
CSO	Combined Sewer Overflow
SWMM	Sustainable Stormwater Management Model
CN	Curve Number
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
TRACI	Tool for the Reduction and Assessment of Chemical and other Environmental Impacts
ISO	International Organization of Standardization
HDPE	High Density Polyethylene

LIST OF SYMBOLS

SYMBOLS

CN_N	Normalized Curve Number
A_i	Area of each sub-catchment
A_T	Total area
S_D	Soil moisture
I_a	Initial abstraction
R	Runoff
P	Precipitation
V	Volume of runoff
f_p	Infiltration capacity
f_f	Final infiltration
f_0	Initial infiltration
k	Exponential decay constant
t	Time
Z	Skew factor
L	Lenght
A_m	Larger area
i	Rainfall intensity
q	Runoff flowrate per unit area
d_s	Depression storage

CHAPTER 1

INTRODUCTION

The natural water cycle includes precipitation, infiltration, surface runoff, and evaporation, which are sustainable processes. The natural water cycle has been severely impacted by urbanization and population increase, particularly at the evaporation and infiltration stages. More runoff water is consequently diverted into traditional water management systems. The quality and quantity of water that is accessible for diverse uses are significantly impacted by these changes in the water cycle in addition to raising the risk of flooding. Flooding will result from increased runoff. The predominance of impermeable surfaces in metropolitan areas, which prevents infiltration and causes fast discharge into the public drainage system, is the main contributor to increasing runoff. In regions with higher impermeable surfaces are also susceptible to flash floods which can happen without warning and cause damage to infrastructure as well as other hazards such as landslides and mudflows [1]. These floods are brought on by intense precipitation that occurs over a brief period of time [2], and they can endanger infrastructure and human life due to their high-velocity runoff and rapid increase of water and silt [3]. Flash floods and landslides are now recognized as significant disasters worldwide [3]. In most cases, flash floods result from a combination of weather and geomorphological factors [4]. Impervious surfaces, such as roads and buildings, prevent rainwater from seeping into the soil and instead force it to flow on the surface until it reaches a drainage point. When rainwater can penetrate the soil, it helps to recharge groundwater, regulate water levels in rivers and streams, and filter out pollutants. However, as the amount of impervious surface increases, the volume, speed, temperature, and pollutant levels of rainwater runoff also increase. As a result, receiving bodies of water may experience flooding, the movement of silt, fertilizers, and contaminants, as well as an increase in water temperature [5].

Impervious surfaces affect the availability and quality of water supply resources. When rainwater is able to seep into the soil, it helps to recharge groundwater aquifers and contributes to base flows in streams and rivers, which helps to regulate their flow during precipitation events. However, impervious surfaces prevent this recharge from occurring, which can result in insufficient water supply for both ground and surface water resources.

Urbanization involves modifying land use, such as removing vegetation, replacing pervious areas with impervious surfaces, and altering drainage channels. These changes inevitably affect the characteristics of surface runoff, resulting in changes to the hydrograph. As a result, the hydrologic behavior of a catchment undergoes significant changes, which in turn affects the streamflow regime. Increases in runoff peak and volume as well as a reduction in peak time are common hydrologic changes in urban catchments [6]. Urban stormwater management has recently faced a problem due to the effects of climate change. Due to global warming, extreme weather events are occurring more frequently in different parts of the world, which conventional stormwater management systems are not equipped to handle. This inability to manage such events increases the risk of flooding, highlighting the unsustainability and lack of adaptability of conventional water management systems [7]. Moreover, the cost of modifying conventional infrastructures to meet the demand is often prohibitively high.

Water scarcity is a significant issue in Cyprus, particularly in the TRNC region, where the annual water shortage amounts to approximately 70-75 million cubic meters, despite the availability of 117.5 million cubic meters available every year [8] at the same time the region is also struggles with frequent flooding, Urban flooding is quite likely to occur in the coastal areas Girne (Kyrenia), Gazimağusa (Famagusta), and Güzelyurt (Morphou) [9]. Additionally, there has been an increase in the frequency of floods with high peak flows, which is thought to be a result of global warming. Guzelyurt, in particular, is experiencing flooding due to inadequate urban design, which lacks impermeable surfaces, resulting in flood

situations in various areas of the town after even minor rainfall events. As a result, traffic issues and harm to private and public properties arise.

Because of urbanization, population growth, environmental consciousness, and the risk of storm surge due to climate change, the usefulness of storm water as a resource during urban development has grown. Alternative approaches to managing urban stormwater have emerged in various countries, such as Australia's Water-Sensitive Urban Design (WSUD), Britain's Sustainable Urban Drainage Systems (SUDS), and North America's Low-Impact Development (LID) [10]. These paradigms recognize stormwater as a valuable resource with multiple benefits for society and the environment, in contrast to traditional drainage methods that prioritize rapid removal. Green infrastructure, also known as low-impact development (LID), offers a strategy for stormwater management that mimics natural hydrology. LID systems, including bio swales, bio retention basins (BRB), permeable pavement systems (PPS), and infiltration trenches, aim to mitigate the environmental impacts of urban stormwater runoff by storing, treating, infiltrating, and evaporating rainfall at its source [11]. By utilizing filter media to remove pollutants, these systems contribute to improved water quality and reduced runoff and peak discharge. Additionally, the implementation of rainwater harvesting systems (RWHS) allows for water storage and future utilization [12]. Despite the availability of extensive knowledge and guidance on sustainable stormwater management practices, their adoption remains limited to demonstration areas and pilot projects rather than widespread implementation [13]. This research is focused on adaptation of SSWMP without any major changes in the existing infrastructure.

1.1 Objective of the Study

The primary objective of this study is to address the negative consequences of urban flooding by implementing innovative stormwater management techniques. The main emphasis is on utilizing low impact development (LID) strategies, such

as bioretention basins, permeable pavement systems, and rainwater harvesting, to effectively control and manage urban flooding. Alongside mitigating the impacts of flooding, this study will also assess the influence of implementing LID strategies on water quality. The study focused on two distinct areas, the first being the campus of METU NCC, and the second being the Güzelyurt Town. These areas have been selected due to their differing characteristics, with METU NCC being a highly urbanized campus environment and Güzelyurt being a densely populated residential district.

LID strategies have emerged as a leading sustainable approach to stormwater management worldwide, but their potential negative environmental impacts must be fully understood. Thus, a life cycle assessment of these LID strategies were conducted, first by comparing different LID strategies to identify those with the lowest environmental impact. The comparison then extended to traditional stormwater management practices, such as resizing stormwater drainage pipes, to ascertain whether LID strategies offer a superior approach in terms of environmental sustainability. Moreover, this study also evaluated the economic feasibility of implementing LID strategies compared to traditional stormwater management practices. It is important to keep in mind that traditional stormwater management practices have been in use for a long time and have a proven track record of being cost-effective. Therefore, this study assessed whether the adoption of LID strategies is economically viable, and if so, the potential benefits that can be derived from their implementation.

1.2 Organization of the Thesis

The thesis is structured into several chapters to provide a comprehensive examination of the utilization of Low Impact Development (LID) strategies for stormwater management and their associated environmental and economic effects. Chapter 1 serves as the Introduction, offering an overview of the problem statement

and research objectives. It emphasizes the significance of LID strategies in mitigating urban flooding and explores the necessity of evaluating their environmental and economic impacts. The chapter also introduces the study areas.

Chapter 2, the Literature Review, critically assesses existing literature on stormwater management, LID strategies, their environmental and economic impacts, and Life Cycle Assessment. It delves into the advantages and disadvantages of LID strategies, emphasizing the importance of conducting a life cycle assessment for LIDs.

Chapter 3, the Study Area, provides a brief overview of the two selected study areas for this research.

Chapter 4, the Methodology, outlines the research methodology, including the study design, data collection, and analysis procedures. This chapter provides detailed information about the two study areas and explains the criteria employed for selecting the LID strategies to be implemented.

Chapter 5, Results and Discussion, presents the study's findings, including the impact of LID strategies on urban flooding and water quality. It also examines the environmental and economic implications of LID strategies, comparing them to conventional stormwater management practices.

Chapter 6, Conclusion and Recommendations, summarizes the key findings of the study and draws conclusions based on the research objectives. This chapter offers recommendations for future research and highlights the policy implications derived from the study's outcomes.

CHAPTER 2

LITERATURE REVIEW

A continual process of water exchange between the atmosphere, land, and water bodies is known as the hydrological cycle, commonly referred to as the water cycle. About 97% of the water on Earth is held in the oceans, and only a small portion is accessible as freshwater. When precipitation falls on land, it can go via a number of different paths, such as evaporation, ground infiltration, and surface runoff. However, impermeable surfaces brought on by development change how water moves naturally, causing surface runoff to rise and groundwater infiltration to fall. The availability of fresh, clean water for people, animals, and aquatic ecosystems is one of the major effects of these hydrological shifts [14]. Urbanization has affected many locations throughout the world and has had a substantial impact on hydrological processes. It is critical to understand how urbanization alters the natural water cycle by adding impervious surfaces, creating artificial flow paths, and removing vegetation, which results in decreased infiltration, decreased water storage capacity, increased surface runoff, and issues with water quality [15]. The imperviousness or concretization of areas is known to have a significant impact on the water cycle, as evidenced by Figure 2.1. In forested areas with no impervious surfaces, the hydrological cycle works naturally, with 100% rainfall assumed to occur. Approximately 40% of this rainfall is taken up by evapotranspiration, while around 50% is infiltrated into shallow and deep groundwater systems. The remaining 10% is lost to runoff. However, as the imperviousness of surfaces increases, such as in urban areas, infiltration and evapotranspiration decrease, while runoff increases. When imperviousness ranges from 75% to 100%, runoff accounts for approximately 55% of rainfall, which can ultimately result in urban flooding.

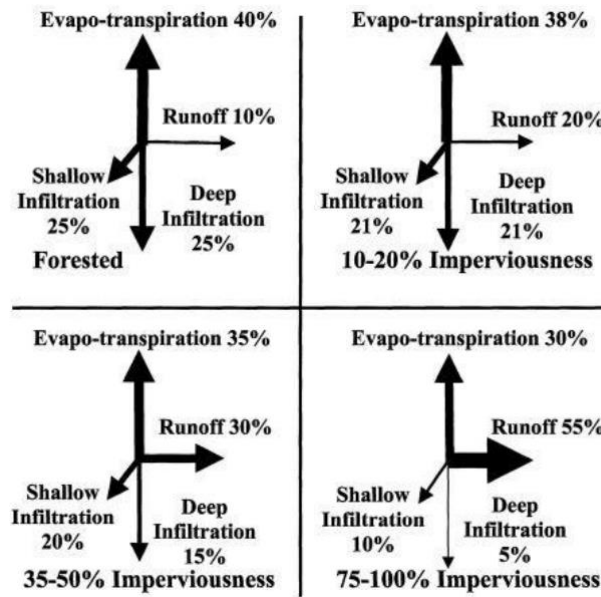


Figure 2.1. Changes in Hydrological cycle with increasing percentages of Imperviousness [16]

2.1 Managing Stormwater and Addressing Urban Flooding

Infrastructure for stormwater management and flood control can be divided into three categories [17], including storage facilities like lakes, ponds, and detention/retention basins, as well as other control structures like gates, locks, levees, and berms. Conveyance channels and conduits include streams, canals, pipes, and streets. System design, operation, and maintenance are to blame for the infrastructure associated to stormwater and flood management that is vulnerable to climate change. Engineering must take into account the non-stationarity of historical precipitation and how it affects the choice of design storm magnitudes [18]. Stormwater and floodplain researchers also need to keep an eye on how the system reacts to storms with high winds, more extreme weather, and early spring flows. Increased floods, combined sewer overflow (CSO), erosion, and different stormwater pollutant concentrations are only a few of the effects of climate stresses on urban drainage systems [19]. These effects vary by region and level of

urbanization. Climate model predictions indicate that runoff may increase up to 40% by the year 2050 in some regions while decreasing up to 30% in others [20]. The IPCC models predict that rainfall intensity will increase in many cities, resulting in an increased incidence of flooding and CSO events. Climate change is predicted to result in daily CSO discharges in the Great Lakes region increasing by up to two times annually. Flooding and combined sewer surcharging are predicted to occur twice as frequently if existing stormwater management techniques remain the same in the future and an extreme precipitation quantile shift of 30% takes place [21].

Flooding can have a significant economic impact on communities, with flood damage increasing not linearly, but disproportionately with flow rate increases [22]. It is crucial to take climatic variability and long-term change into account when planning, designing, and operating stormwater and flood control infrastructure because these systems are often built without taking climate change into account [23]. Each region's vulnerability assessments and adaptation plans are distinct, and they call for interdisciplinary cooperation from a range of stakeholders. The use of hydrologic and hydraulic models to simulate extreme events, routine drainage system performance testing, stormwater harvesting and reuse, retrofitting existing stormwater storage facilities, best management practices implementation, upgrading suitable green infrastructure, and educating homeowners about water conservation are all examples of adaptation strategies [24].

2.2 Challenges with Traditional Stormwater Management

Historically, the conventional approach to stormwater management involved removing stormwater from urban areas through flushing measures, resulting in reduced ground water infiltration and negatively impacting ground water levels. However, conventional systems are not equipped to handle extreme weather events brought on by global warming, leading to an increased risk of flooding [25]. To

address this, Sustainable Storm water Management practices have introduced which are decentralized systems that have demonstrated increased feasibility and cost-effectiveness. than traditional centralized approaches for storm water quality treatment [26]. Additionally, because conventional systems are mostly underground and unseen, people are less aware of and accountable for the water cycle. Urban areas alter the entire river system, causing eutrophication and pollution to travel downstream, which also affects the natural system. The rational method used for designing a storm water network for an urban area is not suitable for dealing with extreme events caused by global warming, as existing drainage systems are not capable of handling higher rainfall intensities without causing flood situations. Instead of simply enlarging infrastructure, reducing peak discharge through techniques such as Sustainable Storm water management, low impact development (LID), and green infrastructure (GI) is a more sustainable and effective solution to address the issue.

2.3 Low Impact Development Strategies

Promoting site penetration and restoring ecological integrity in urbanized settings are the goals of cutting-edge strategies that prioritize Low Impact Development (LID) practices. A cost-effective infrastructure management approach is produced by LID practices, which integrate system design, engineering, and land use planning [27]. The fundamental tenet of LID is to maintain hydrologic conditions near to those that existed naturally before industrialization. LID techniques aim to lessen stormwater runoff and enhance water quality while lowering the cost of building, running, and maintaining infrastructure [28]. Through the permeation and recharge of rainfall into the underground, LID methods can lessen their influence on the environment. Infiltration trenches, continuous permeable pavements, bioretention cells, rain gardens, green roofs, rain barrels or cisterns, rooftop disconnections, and vegetative swales are a few of the techniques used [29]. LID techniques can assist reduce blight and land fragmentation while also raising public

awareness of urban problems. To regulate the rainstorm's source, these systems can build a sophisticated but effective infrastructure throughout the area [30]. Designing LID practices with a linked urban system in mind will enable the facilities to be effective from an ecological and sustainable standpoint. The three main facets of LID activities are collection, delivery, and cleaning. LID approaches have significant benefits for urban development and hydrology, such as reducing stormwater runoff, enhancing water quality, and lowering construction and maintenance costs. Stormwater runoff reduction is one of LID practices' key advantages. As rainwater gets closer to the natural water cycle, these methods might collect and penetrate it, which is important for urban hydrology [31]. LID methods can return runoff to the natural water cycle, reducing total runoff, enhancing infiltration, reducing peak flow, and lengthening lag time [32] compared to traditional stormwater management in urban environments. Ecosystems on the surface and below the ground need rainwater, which is a valuable natural resource [33]. Additionally, LID techniques can raise water quality, a crucial performance parameter. Urban rainfall reduces aquatic life levels as a result of global warming, which alters storm frequency and pattern significantly as a result of rising atmospheric greenhouse gas concentrations [34]

Additionally, LID techniques can aid in addressing social, economic, and environmental issues, resulting in the creation of a sustainable living environment on a broad scale. The collection role entails lowering stormwater runoff and enhancing the local waters. The delivery function entails channeling runoff from storm drains to other structures that may collect and store precipitation. The water can then be moved to the pond, where it is treated using a filter system. In order to offer clean and healthy water, the cleaning function can filter and purify rainwater that contains excessive pollution and suspended particulates. Freshwater habitats and water quality suffer from urbanization. Because of the compacted subsurface soil, altered soil structure, and decreased soil infiltration capacity brought on by development operations, the hydrological pattern of the landscape has changed, and stormwater runoff has increased in velocity and flow. In order to establish a

sustainable living environment that takes into account environmental, economic, and social factors, LID methods must be put into effect.

2.3.1 Categories of Low Impact Development Strategies

Bioretention Cell

Stagnant landscape areas that treat and attenuate stormwater runoff are often called as bioretention cells or may be as rain gardens and are becoming increasingly popular in residential and commercial settings [35]. These terms are used interchangeably, although bioretention cells are designed to retain captured stormwater through filter media, resulting in a decrease in runoff volume [36]. Their stormwater infiltration capabilities stem from Their capacity to postpone runoff during periods of peak percolation. Furthermore, plant evapotranspiration within bioretention cells can also contribute to reduced stormwater outflow. The porous filter media in bioretention cells are crucial for decreasing stormwater pollution in addition to reducing runoff. As shown in Figure 2.2, bioretention systems use a combination of surface ponding, vegetation, soil layers, storage layers, overflow structures, and optional underdrain systems to manage stormwater runoff. Individual bioretention cells' designs can differ and have a significant impact on how well the system works. In addition to design, the construction approach, location, and maintenance can impact system performance. Literature on bioretention system design highlights their hydrological and pollution effects. The system's soil media is crucial for runoff reduction, and an infiltration rate of 25-50 mm/h is recommended [37]. The taxonomy and structural diversity of plants should be planted for the best outcomes since vegetation type substantially affects hydrological efficiency. Longer periods of rainfall with lower intensities are ideal for bioretention cells. There are several ways to increase the purity of stormwater released from bioretention cells, including establishing an anoxic zone using

materials like wood chips, newspaper, sulfur, or sulfur dioxide, establishing a saturated zone, and adding P sorption materials.

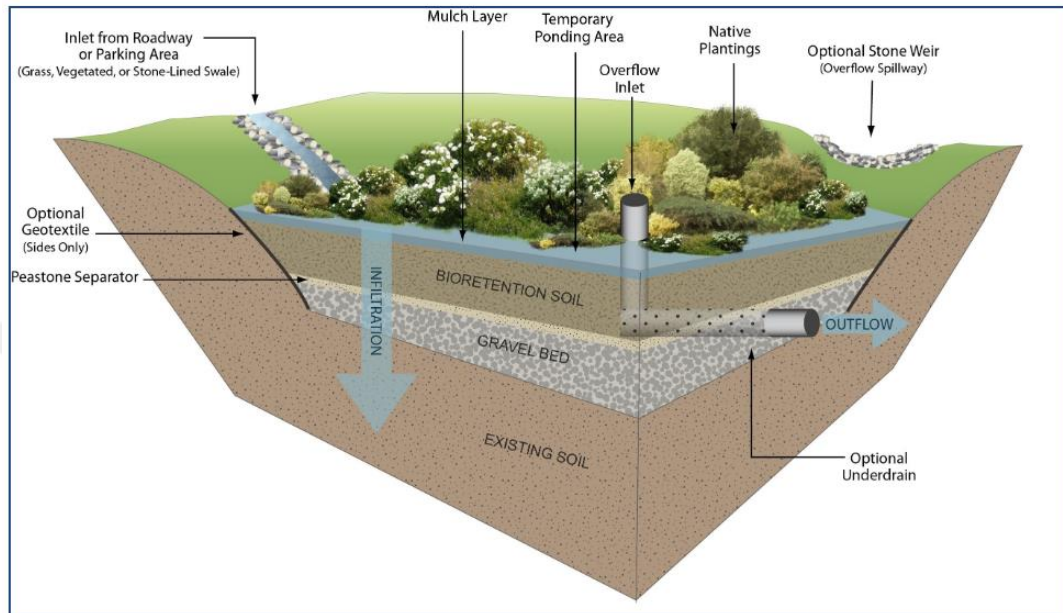


Figure 2.2. Design features of Bioretention areas for effective stormwater management [38]

The capacity of contemporary bioretention systems to reduce stormwater runoff volume has been validated by several field investigations carried out in diverse places. For instance, after a series of rainfalls, bioretention cells in Maryland produced flow peak reductions ranging from 44% to 63% [39]. In a similar vein, it was discovered that a bioretention system in Mexico with sandy loam soil, succulent plants, and herbaceous grasses had absorption rates between 2.25% and 5.37% of runoff volume [40]. An experimental rain garden in Xi'an, China, was found to lower overflow rates for 23 out of 28 significant storm events by between 77% and 94% [41]. Additionally, it was discovered that rain gardens considerably lessen the adverse hydrological effects of the built environment. For three different rain gardens, longer-term research reported average runoff volume reduction rates of 60.0%, 97.8%, and 96.3% [42]. Systems using bioretention can typically manage at least 60% of runoff [43]. The high hydrological efficiency of bioretention

systems is reliant on the size of rainfall events, with little or medium rainfall episodes having a greater impact than big rainfall events.

It has been demonstrated that bioretention systems not only improve hydrology but also lower the levels of a number of contaminants, such as oil and grease, heavy metals, and total suspended particles [44]. The 13-month monitoring of bioretention systems revealed that 84% TN and 50% TSS were maintained [45]. The rates of bacteria elimination in bioretention systems were discovered to range from 70% to 99%. Additionally, according to research, bioretention systems can remove copper, zinc, and lead by up to 98% [46]. In addition to lowering pollution loads and enhancing groundwater recharge, bioretention systems also reduce surface runoff and encourage infiltration. They also provide ecological benefits by maintaining plant and wildlife populations and are adaptable enough to be used in a variety of building situations. In addition to these advantages, bioretention systems can improve microclimates by assisting in cooling and boosting humidity on hot days, thereby reducing the intensity of urban heat. This microclimatic advantage, combined with the aesthetic enhancement provided by bioretention systems, can have social benefits by improving the comfort level of urban residents [47]

Green Roofs

The use of green roofs as an alternative to conventional, impermeable roof surfaces is growing. They are made up of a waterproofing membrane placed on top of a layer of flora. Green roofs, often referred to as living roofs, eco-roofs, or vegetated rooftops, are frequently utilized to make up for the loss of native vegetation resulting from building construction [48]. Green roofs are a key component of Low Impact Development (LID) strategies that significantly lower stormwater runoff. They accomplish this by combining storage in the green roof media with evapotranspiration, which happens through the roof's plants [49]. When it rains, green roofs capture some of the moisture and store it as a buffer in the soil layer. The soil's capacity determines how much of the retained water is stored and how

much is discharged. The plants then gradually extract the part that is still in the soil by evapotranspiration [50]. The capacity and rate of stormwater retention of green roofs are frequently used to measure how well they manage stormwater. The retention rate is the percentage of rainwater that is held during rainfall events, whereas the retention capacity refers to the maximum amount of precipitation that the green roof can keep. These performance metrics can be impacted by a number of variables, including precipitation intensity, roof characteristics, medium composition, thickness, plant species, and climate conditions [51].

Typically, a waterproof membrane on the roof is covered with a drainage layer, a growing substrate, and flora to create a green roof [52]. Based on the thickness of the substrate layer, green roofs can be categorized as intensive or extensive [53]. In order to support the growth of plants with larger root systems, including small trees, intensive green roofs include substrate layers that are deeper than 15 cm. In contrast, extensive green roofs can only support shorter-rooted plants since their substrate layers are less than 15 cm thick. Due to their greater affordability, lighter weight, quicker installation, and lower maintenance requirements when compared to intensive systems, extensive green roofs are more frequently used. According to research, the capacity of green roofs to hold and release rainwater is substantially impacted by the thickness of the soil layer. Therefore, it is believed that intensive green roof systems perform better than extensive systems in this regard [54]. Extensive green roof systems can, however, have a benefit when retrofitting existing roofs because of their lesser weight, which enables them to cover more areas without overloading the structures made for smaller loads. The use of permeable substrate layers is advised in order to increase the stormwater performance of green roofs by enhancing stormwater infiltration and lowering runoff and substrate erosion. Additionally, increased permeability improves root ventilation for plants, reducing rotting [55]. The choice of plant species has a big impact on how well green roofs retain and discharge runoff. When choosing plants for green roofs, designers should take into account how the chosen substrates and plants interact with one another [56]. The microclimate of the green roof's site

should also be considered to ensure the installation's success because the right plant species are essential to the effectiveness of green roofs. Additionally, choosing plants with higher transpiration rates will help design for enhanced evapotranspiration, which increases water retention. Every design should take into account the various elements that affect how much stormwater is retained by green roofs. The green roof's pitch is crucial because steeper slopes often have poorer retention [57]. Retention levels can also be impacted by increased rainfall amounts and weather factors like preceding dry days. It is also paid that the composition of the green roof medium largely impacts pollution retention, significant consideration should be paid to the design of green roof systems in order to reduce pollution [58]. According to numerous studies in the literature, green roofs function well under a variety of climatic circumstances. These investigations have found that rainfall retention can range from 20% to 100% [59]. In a more recent investigation, 16 experiments were conducted using two basic combinations of two plant species in the presence of natural rainfall, and the average stormwater retention was determined to be 77% [60]. Another study found that Sedum linear planted on a 15-cm-thick substrate retained stormwater at a rate of 77.2% [56]. In a further study, researchers looked at how well two different vegetation types retained precipitation. They discovered that sedum mix performed much better than sedum mix with indigenous, with retention rates of 47% and 61%, respectively [60]. Using the same vegetation type (Sedum mix), they also looked into how media thickness affected precipitation. They found that a 3.2-cm-thick media retained 36% of water and a 10-cm-thick media retained 61%. Stakeholders continue to voice concerns about runoff pollution from green roofs. According to one type of study, average total suspended solids (TSS) concentrations in runoff from green roofs were higher than those in runoff from conventional roofs (12.08 mg/L) and average total nitrogen (TN) concentrations were higher than those in conventional roof runoff (0.59 mg/L) [61]. These results show that green roofs significantly contribute to runoff pollution. Studies on the effects of pollution from green roofs, however, have produced a range of outcomes, from increased pollution to decreased

pollution. These variances in performance can be due to the different ways that green roofs are designed, which have a big impact on them.

In addition to retaining stormwater runoff, green roofs also improve air quality, boost biodiversity, conserve energy, improve urban aesthetics, lessen the effects of urban heat islands, and encourage urban cooling. Furthermore, as there are frequently a lot of empty rooftops accessible, the building of green roofs is not limited by a lack of space. However, compared to large-storage rainwater harvesting systems, green roofs may be less effective as a Low Impact Development (LID) technique for minimizing stormwater runoff. In some cases, green roofs can also contribute to stormwater pollution. However, this pollution can be reduced by using appropriate designs and using the right building materials for each green roof installation. The conventional design of a green roof is depicted in Figure 2.3.

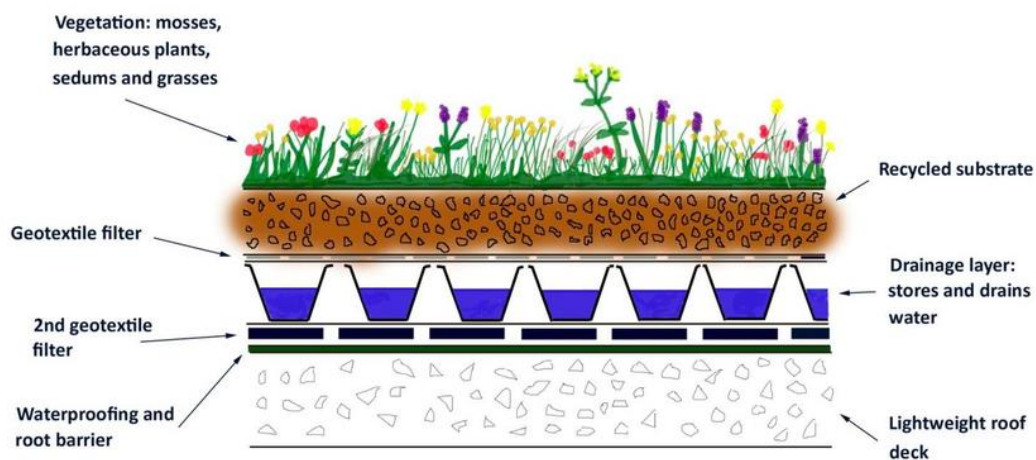


Figure 2.3. Typical design of a Green Roof [62]

Infiltration Trench

An infiltration trench is an underground structure containing porous and permeable materials, designed to enhance underground infiltration capacity and manage urban stormwater [63]. Infiltration trenches serve multiple purposes, including reducing

urban runoff, increasing groundwater volumes, and improving water quality. They can reduce surface runoff by approximately 10% of rainfall [64]. Typically linear in shape Permeable materials like gravel, sand, stone, and filter fabric are utilized in infiltration trenches to regulate the flow rate of surface water. These trenches facilitate groundwater recharge and partially trap contaminants within the structure, thereby mitigating groundwater pollution. Figure 2.4 shows the typical design of infiltration trenches.

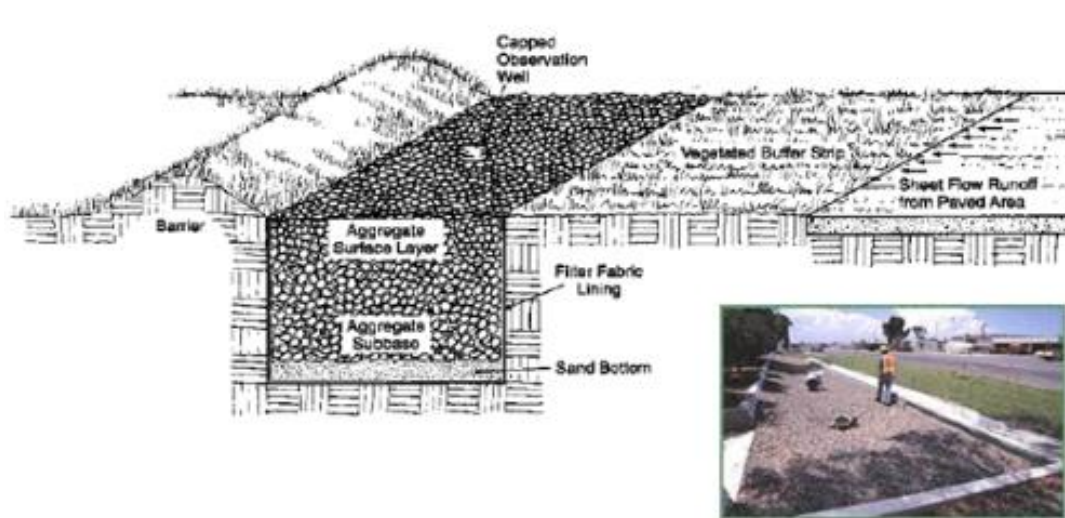


Figure 2.4. Design drawing for Infiltration Trench [65]

Infiltration trenches are considered structural management systems for stormwater runoff and can be implemented in various spaces, including underground pipes, to mitigate pollution impacts. Geotextile materials will also be incorporated into the system to prevent sediment-induced clogging during construction. However, it is important to note that infiltration trenches are more suitable for small, frequent storms, as clogging issues may arise with larger storm events [66]. In order to increase infiltration velocity and pollutant filtering during intense rainstorms that produce more water than the infiltration system can store, bypass flow systems should be taken into consideration. The use of infiltration trenches is not advised in highly contaminated locations because it may jeopardize groundwater pollution control. The efficient operation of infiltration trenches depends on routine

inspection and maintenance. The system should be checked after each rainfall event during the initial months, and inspection wells should be installed for surface observation. Over time, clogged aggregates and contaminants can reduce infiltration efficiency, necessitating periodic changes in trench fields. To improve treatment efficiency, regular inspection of the entire infiltration trench system should be conducted at least twice a year to ensure proper functioning [66]. The main objective of an infiltration trench is to capture surface runoff and mitigate flooding problems in urban environments. These trenches are typically designed in rectangular shapes with dimensions tailored to specific site conditions. Typically, the width falls between one and a few meters. Filtration materials like gravel and sand are placed in the infiltration trench's main part. Depending on the site conditions, the thickness of each material can vary. Fine gravel should be 0.25 meters thick from top to bottom, whereas sand should be 0.10 meters thick [67]. Smaller than fine sand particles in varied ratios make up the filtration material. The porous materials are additionally filled by a perforated pipe, which is optionally encircled by a geotextile material. It is anticipated that the infiltrated stormwater will enter a stream right away. High groundwater tables and low hydraulic conductivity in the soil, for example, have an impact on how well an infiltration trench performs.

The infiltration capacity is a significant parameter to assess performance, and comparisons have shown that infiltration trenches generally have a higher capacity than infiltration ponds [68]. In cases where a shallow groundwater table exists, the infiltration capacity of the trench may be diminished. In such circumstances, the effectiveness of the trench in managing stormwater runoff and reducing peak flow is evaluated by examining the reduction in both peak flow rates and stormwater runoff volumes. These indicators are used to assess the hydrological performance of the trench under such conditions. The infiltration trench is widely recognized for its benefits in groundwater recharge and reduction of environmental pollutants. It plays a crucial role in mitigating stormwater runoff and maintaining a safe groundwater table. Excessive extraction of groundwater without replenishment can

lead to land subsidence, particularly in coastal cities. Infiltration trench systems are crucial for supporting year-round groundwater recharging and restoring the natural hydrologic cycle.

Infiltration trenches serve as low impact construction and green infrastructure measures that lessen pollution delivery to groundwater in addition to groundwater recharge. The combination of gravel and sand in the trench enables physical filtering, removing bigger pollutants and raising the catchment area's water quality. When rainwater persists in the detention and retention zones, there are worries about the possibility of groundwater pollution. Groundwater quality may be at risk in places with sandy geology and shallow groundwater levels because pollutants may not have enough time to degrade or bind to soil particles [69]. To overcome the possible drawbacks of infiltration trench systems, such as clogging and potential shortcuts, proper stormwater management is essential. The permeability of porous materials in the trench can be greatly reduced by sediment deposition, which can result in clogging. Lack of inspections and maintenance can exacerbate these issues and may require the replacement of clogged aggregate. Clogging rates and system lifespan vary depending on local stormwater and site conditions. To effectively manage urban stormwater, it is important to improve maintenance practices and increase awareness of the maintenance needs of metropolitan areas.

Permeable Pavements

The management of urban stormwater runoff and the lowering of environmental pollution can both be accomplished with permeable pavement. It performs the function of a porous infrastructure interface, capturing and infiltrating surface runoff and replenishing groundwater. Typically, the building is made up of a filter layer and a concrete paver. By allowing stormwater runoff to infiltrate and evaporate, this sustainable infrastructure material supports hydrologic restoration and pollution management [70]. The goal of integrated urban rainwater management is to preserve the natural water balance and flow patterns while

reducing the adverse effects of urban rainwater, such as the deterioration of groundwater quality and recharge losses. By locally regulating rainwater at the source and mimicking pre-development site conditions, permeable pavement plays a critical role in attaining these objectives. Developers and municipal governments looking for sustainable solutions for cities have started to pay attention to it. In a number of experimental schemes, permeable pavement has been used in pedestrian walkways and parking lots in low-traffic regions. It can also act as smooth-surfaced load-bearing infrastructure for low-speed vehicle movement. To lessen road noise, it is occasionally utilized as a porous highway overlay. Under various circumstances, the porous nature of permeable pavement enables the mitigation of big design storm flows and environmental pollutants. The widespread use of permeable pavement, however, confronts some difficulties. There is still a lack of understanding regarding runoff infiltration's long-term effects on the environment, particularly during cold weather. Without enough testing for longevity, sustainability, and maintenance costs, developers and engineers might be hesitant to put the idea into practice. Another problem with porous pavement systems is clogging, and to prevent it, appropriate installation and routine maintenance are required. To restore permeability, clogged materials can be removed using a vacuum sweeper and pressure washing [71]. To enable proper implementation of permeable pavement and handle potential issues, design guidelines and restrictions must be provided. Permeable pavement has not been widely used in Canada or the USA despite its potential advantages, highlighting the need for greater awareness and comprehension of its long-term performance and environmental implications.

An approach to stormwater management known as pervious pavement permits water to seep through its material matrix or open voids [71]. A porous pavement system's construction typically consists of one or more beneath gravel layers and a permeable paving surface. Porous aggregate, porous grass, plastic geocells, open-jointed paving blocks, open-celled paving grids, porous concrete, porous asphalt, soft paving materials, and epoxy-bonded porous materials are just a few of the surface paving materials that can be utilized to create permeable pavement. As

reservoirs for aggregate, the subsurface gravel layers [72]. Geotextiles, small aggregate filters, and choker courses may also be included in the permeable pavement system design as additional elements. Existing permeable pavement materials come in a variety of forms, each with unique functional, environmental, esthetic, and financial needs. The three materials that are most frequently utilized in commercial applications are porous asphalt, permeable concrete, and interlocking concrete pavers [72]. While permeable concrete and porous asphalt allow water to pass through the binder-covered aggregate particles, permeable interlocking concrete pavers are filled with open-grade aggregate and have modular unit separation joints. In order to accomplish full or partial penetration, the design of a permeable pavement system comprises the selection of suitable border components based on site characteristics. To enable efficient infiltration through the paving surface, the permeability of the pavement layer should be greater than the intensity of the rainfall. When filtration is not required, seepage can be collected and transferred directly to the drainage system using subterranean drains with perforated pipes that are installed close to the bottom of the aggregate reservoir [72]. Exfiltration [73] is the term used to describe the rainfall collection through the porous permeable pavement system and discharge into the subterranean sewers. Some parking lots with permeable pavement may have vault storage to control outflow and stop leaks. However, raising the bottom drain over the inverted arch of the catchment floor may raise the possibility of local overflow.

Additionally, the soil and climate of the area should be taken into account while designing a permeable pavement system. Sites with contaminated soil might not be appropriate for installing the system because there is a possibility that it will contaminate the groundwater. Using deicing salts in cold regions can also have an adverse effect on the environment since chloride, in particular, is predicted to permeate the pavement layer and raise the concentration of chloride ions in groundwater [73].

Hydraulic conductivity and durability are two factors that can be used to assess permeable pavement performance. The performance of the porous pavement system can be affected by elements including the local climate and geological conditions, including shallow groundwater. The system's design modifications, notably the types of underdrainage components, can also affect how well it works. The hydrological performance of permeable pavement is influenced by various factors, including outflow volume, peak flow, timing, and frequency [73]. Key aspects of hydraulic performance encompass runoff attenuation, surface infiltration capacity, and peak reduction. The most crucial hydraulic property of the porous pavement system is hydraulic conductivity, which is impacted by pore structure [74]. Evaluating the system's performance requires considering hydraulic conductivity, along with runoff data and historical rainfall volume. This indicates that infiltration-based practices are more effective for smaller, more frequent stormwater events [74]. To analyze the variables of permeable pavements and rainwater, hydrologic and hydraulic simulation systems can be utilized.

In terms of longevity, the durability of the porous permeable system is contingent on its ability to meet hydrological and water quality requirements [72]. Structural failures such as rutting and cracking can lead to diminished permeability and pollutant removal capacity. Aging pavements may fail to meet necessary standards, including hydrological, water quality, aesthetic, and safety aspects. Clogging and maintenance significantly influence the lifespan of the porous permeable system [71]. Over time, fine particle filtration can reduce pavement permeability, but regular maintenance can help mitigate this issue. If precipitation rates exceed infiltration rates, water accumulation and surface runoff may occur, diminishing the eco-friendly benefits of permeable pavement, such as peak flow reduction and rainwater contaminant removal. Therefore, regular surface maintenance and blockage removal are crucial to ensure continuous hydrological and water quality performance. Frost effects should also be considered during maintenance, as the freeze-thaw cycle can cause pavement damage in cold climates [75]. Figure 2.5

illustrates the typical design of permeable pavement, highlighting its key elements that enhance permeability and improve the water quality of runoff.

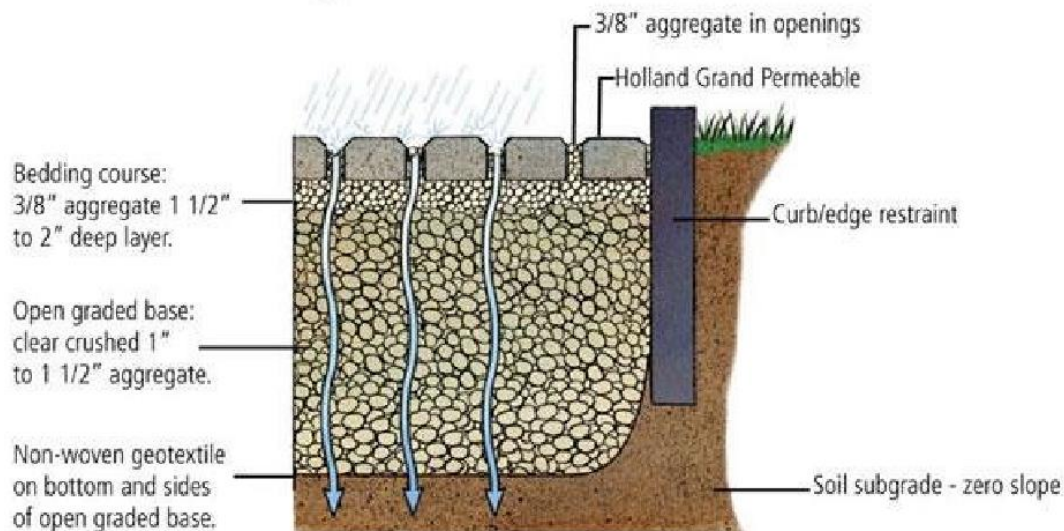


Figure 2.5. Typical design of a Permeable Pavement [76]

It has been demonstrated that the use of permeable pavement lowers pollution loads and storm runoff [31]. The porous pavement technology has the ability to enhance groundwater quality by treating stormwater in terms of water quality [72]. The system's base and paving surface filters absorb and filter a variety of pollutants, such as suspended particles, nitrogen, and heavy metals [51]. The porous pavement system can help reduce rainfall nutrient levels, which can cause eutrophication.

Rain-water Harvesting or Rain Barrel

In order to manage stormwater effectively, rain barrel systems gather water from urban rooftops during storm events. The collected rainwater can then be used for domestic water supplies during dry spells [77]. Residential uses for rainwater collected from rain barrel systems include flushing toilets, drip irrigation, and washing clothes. Rain barrels can also be used to collect water for non-potable uses including gardening, watering lawns, and recreation. They aid in lowering water pollution and peak flow volume [78]. Rain barrels can also be incorporated into

beautiful designs and are generally put in unassuming settings like parking lots and the corners of backyards. Comparatively speaking, rain barrel systems require less upkeep than conventional infrastructure-based water management facilities [78]. Cleaning gutters and storage tanks are typical maintenance tasks for rain barrels. One key aspect of domestic rainwater gathering programs is that rain barrel systems must be operated and maintained by homeowners. However, because there aren't any national standards for rain barrel design, installation, and maintenance, or for the water quality principles that apply to this resource, local government health agencies frequently have the authority to enact rules [78]. For some homeowners, the variety of rules and upkeep specifications may make rain barrel systems less popular and less effective. It is advisable to perform regular roof cleaning for rain barrel systems, although research indicates that even with minimal maintenance and cleanliness, water quality analysis demonstrates low levels of pollutants such as total suspended solids and total organic carbon [79].

A catchment surface (such a building roof) that collects rainwater, a rain gutter to direct the water, a storage container, a network of pipes linking the catchment surface to the storage container, and an overflow system are the basic elements of a rain barrel system [79]. The specifics of a typical rain barrel arrangement are shown in Figure 2.6. To improve the quality of the water collected, some rain barrel systems might also include a filter system or a first flush device [80]. Polyethylene barrels with a 300 liter capacity are typical domestic water storage containers [80]. Storage tanks for rain barrel systems can be built either above or below ground, utilizing various materials such as bricks, rammed earth, plastic sheets, stabilized soil, mortar jars for smaller-scale storage, and earthenware, polyethylene, concrete, or iron for larger water storage.

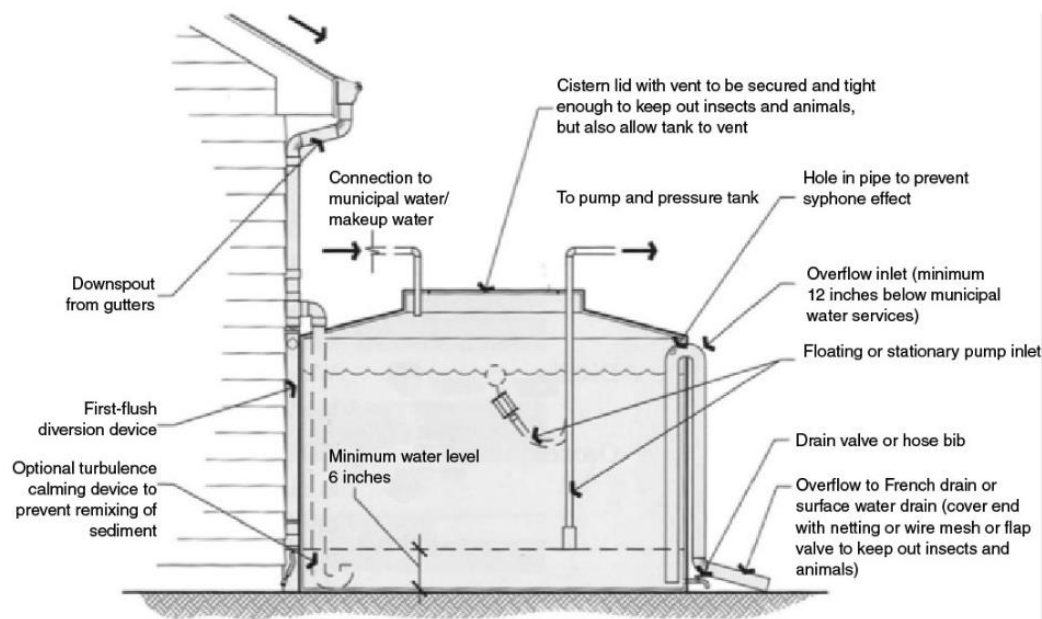


Figure 2.6. Surface rainwater harvesting tank [81]

Installing rain barrels is a practical way to lower runoff volume and enhance the quality of water in residential settings. In commercial or industrial regions, rain cisterns may also be utilized [82]. By capturing runoff and storing rainfall, rain barrels have the unique capacity to augment water demand. This is especially advantageous in places with limited land. To expand storage space for infiltration and irrigation, many barrels can be joined together. Longer-term use is made possible by the fact that larger rain barrels are made to collect runoff from both smaller and larger storm occurrences. Roof slope, storage system material, land use techniques, and weather patterns are only a few of the variables that affect the quality of rainwater collected [83]. The choice of roof material has a substantial influence on the quality of collected water. Conventional roof materials such as concrete tiles, metal, and asphalt fiberglass shingles, along with alternative options like green roofs, can affect the quality of the harvested water. It is essential to periodically flush, filter, and disinfect the rainwater collected from the roof surface to maintain its quality.

Rooftop Disconnection

Rooftop disconnection includes directing water from roof downspouts away from rain pipes and into permeable vegetation and vegetated surfaces [84]. This can be done either by replicating a roof drain that overflows into a permeable region or by draining the water via channels to water catchment sites. The roof surface and downspouts are often included in the design of a rooftop disconnection system, which treats the roof area as impermeable and permits runoff to pass through infiltration regions [84]. Runoff and pollutants are known to be considerably reduced via rooftop disconnection. It can be used on many different types of ground, especially in residential areas where the water can be collected and routed to pervious surfaces like lawns. Rooftop disconnection's usual design is depicted in Figure 2.7.

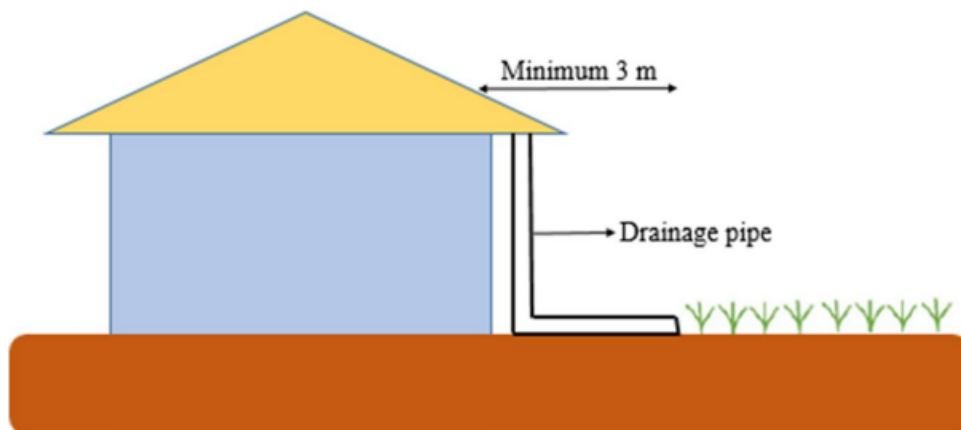


Figure 2.7. Typical Rooftop Disconnection design [85]

Incorporating rooftop disconnection as a passive drainage strategy can effectively contribute to long-term objectives in stormwater management, specifically in mitigating flood risks. Furthermore, rooftop disconnection serves as a preventive measure to minimize the entry of contaminants from residential roofs into the stormwater system.

Vegetative Swales

The vegetative swale, often referred to as a bioswale, is a narrow linear depression that has sloped sides and is used to collect, convey, and filter rainwater runoff [85]. It is frequently used as a method of stormwater management in a variety of urban environments, including urban villages, parks, green spaces, business districts, and roadways. It is regarded as one of the simplest and most uncomplicated low-impact development (LID) strategies that can take the place of conventional curb and gutter drainage systems in terms of construction [86]. The vegetative swale performs a dual purpose in the drainage system by acting as a landscape surface trench. By providing storage space, it not only lowers peak rainfall runoff but also efficiently eliminates all suspended particulates from the runoff [87]. Total suspended solids, a prevalent pollutant in urban runoff, can have a sizable impact on the turbidity of water. Reduced sunlight penetration into the water due to increased turbidity can harm plant photosynthesis. Therefore, in order to lower the total load of suspended solids in runoff, the effectiveness of pollutant removal from surface buildup in vegetative swales is critical. Figure 2.8 shows how vegetative swales are constructed.

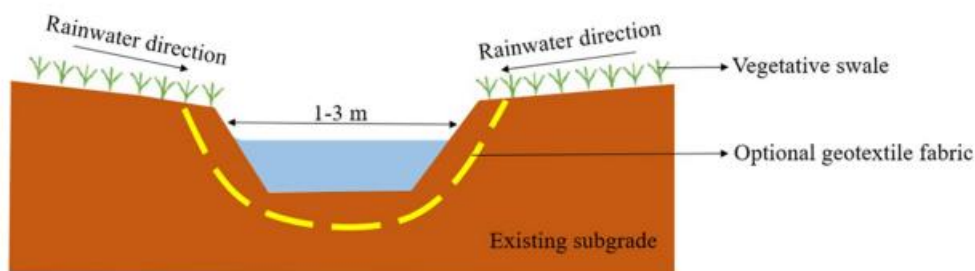


Figure 2.8. Typical Design of Vegetative swales [85]

In order to establish Low Impact Development Strategies and anticipate the quantity and quality of runoff in urban areas, many software programs are used in stormwater management. Several models, including RECARGA, P8 Urban Catchment Model, SWMM, SWAT, and ARNO, have been developed for this

purpose [88]. The Storm Water Management Model (SWMM) was especially used in the current investigation. Both single storm occurrences and continuous simulation can be simulated with SWMM. It can handle a wide range of input data, from simple to extremely detailed, and still produce results that are useful. The model is ideally suited for simulating linked catchments' features since it can aggregate catchment hydrology. Being an open-source program, SWMM has the benefit of being both publicly available and adaptable. The model's website also offers a technical assistance system to help users. Given these advantages, SWMM was chosen as the ideal study program. The literature review on SWMM is presented in the section that follows.

2.4 Stormwater Management Model (SWMM)

The U.S. Environmental Protection Agency (EPA) created the SWMM, a dynamic simulation model for rainfall-runoff, in 1971. It is frequently utilized to model runoff quantity and quality in metropolitan environments, whether for short-term or long-term occurrences. The model includes a runoff component that functions on sub catchments that produce runoff and pollutant loads in response to precipitation. The routing component of SWMM is then used to transport this runoff through pipelines, channels, pumps, and regulators. For each sub catchment, the model determines the quantity and quality of runoff. Additionally, SWMM simulates each pipe's and channel's flow depth, flow rate, and water quality over a number of time steps. It includes a number of hydrological procedures that contribute to runoff production [89]. SWMM, a dynamic modeling tool, possesses the ability to simulate the entire process of rainfall runoff, encompassing both individual storm events and long-term scenarios. This model comprises two primary elements: the computation of runoff generation from various subcatchments, and the routing section responsible for conveying the generated runoff through a network of pipes, channels, storage units, pumps, and regulators.

Different hydrologic processes are used in SWMM, including the characteristics of rainfall, evaporation of standing surface water, snow accumulation and melting, interception of rainfall from depression storage, infiltration of rainfall into unsaturated soil layers, percolation of infiltrated water into groundwater layers, interflow between groundwater and the drainage system, and capture and retention of rainfall/runoff. The model also has the following features in its hydraulic portion, which mimics the movement of runoff through the drainage system [89]. The operations include handling networks of any size, using a wide range of standard closed and open conduit shapes as well as natural channels, modeling special elements like storage/treatment units, flow dividers, pumps, weirs, and orifices, incorporating external flows and water quality inputs from various sources, using either kinematic wave or full dynamic wave flow routing methods, modeling different flow regimes including backwater, surcharging, and more.

Each catchment can be divided into homogeneous sub catchments to account for spatial variability within the modeling system because there is no limit to the number of sub catchments that can be established in the SWMM program. Additionally, utilizing the desired time step, SWMM has the capacity to replicate both the quantity and quality of runoff throughout a given time period, whether it be an incident or long-term. This program's capability to mimic the quality of runoff produced from sub catchments and determine the pollution levels within the runoff is one of its standout features. However, because the quality of runoff is not the main focus of this study, specific information has not been supplied. The SWMM model encompasses the essential components of a rainfall-runoff system, which are represented by three main elements: rain gauges, subcatchments, and the conveyance section. These components collectively simulate the physical aspects and interactions within the system.

SWMM provides the ability to model the following processes for any number of user-defined water quality constituents, in addition to modeling the formation and

transit of runoff flows and estimating the production of pollutant loads associated with the runoff [90], below are some of its operations.

- Accumulation of pollutants during dry weather periods in various land uses
- Runoff of pollutants from specific land uses during storm events
- Direct contribution of pollutants through rainfall deposition
- Decrease in dry-weather pollutant buildup through street cleaning practices
- Reduction in pollutant wash-off load due to the implementation of Best Management Practices (BMPs)
- Incorporation of dry weather sanitary flows and external inflows at any location within the drainage system
- Transportation of water quality constituents throughout the drainage system
- Dilution of constituent concentration through treatment in storage units or natural processes in pipes and channels.

Since its creation, SWMM has been extensively used in a number of sewer and stormwater studies all around the world. SWMM has several typical uses, such as:

- Determining optimal sizes and designs of drainage system components to effectively manage and control floods.
- Sizing detention facilities and associated structures to support flood control efforts while ensuring water quality preservation.
- Mapping floodplains in natural channel systems to evaluate potential risks and vulnerabilities.
- Formulating strategies to minimize combined sewer overflows.
- Assessing the influence of inflow and infiltration on sanitary sewer overflows.
- Estimating pollutant loadings from non-point sources for waste load allocation studies.
- Evaluating the efficiency of Best Management Practices (BMPs) in reducing pollutant loadings during wet weather conditions.

Runoff must be computed for the stormwater network design, and precipitation data must be used. The main input for the runoff simulation model used in SWMM is precipitation. Precipitation data can be added into SWMM either by specifying time series or by utilizing an external data file [90]. Both discrete rainfall episodes and long-term records of continuous precipitation can be simulated using the model. In order to simulate snow melt or calculate potential evapotranspiration if the Hargreaves technique is used, air temperature data is also needed by SWMM. A user-generated or downloaded climate data file may be used to represent temperature data as a time-dependent set. The SWMM takes into account evaporation from a number of sources, including water on sub-catchment surfaces, underground water in groundwater aquifers, water flowing in open channels, water stored in storage units, and water from low-impact development restrictions. Evaporation is not essential for single event simulations, but for continuous simulations, it becomes necessary for calculating the water budget. A single constant value, a group of monthly average values, a user-defined time series of daily values, or data from an external climate file can all be used to describe evaporation rates. If the research area's latitude and the daily maximum-minimum temperatures are known, the Hargreaves method can be used to determine evaporation rates.

Wind speed is taken into account in SWMM to more precisely calculate snow melt rates when rainfall occurs in an area where snow has collected. The same climate file used for daily temperature and evaporation data can also be used to collect wind speed data, which can be delivered as monthly average values [89]. The rainfall-runoff dynamics in the Runoff Block of SWMM are the main subject of this study. For hydrological simulation within the Runoff Block, these processes require a number of modeling input data, including precipitation, area, imperviousness, slope, roughness, width, depression storage, and infiltration characteristics [89].

A distributed model called SWMM is used to calculate surface runoff from rainfall. The research region has been divided into sub-catchment areas, and SWMM simulates the quantity of runoff within each sub-catchment by taking into account the spatial heterogeneity in topography, drainage pathways, land cover, and soil properties that affect runoff generation. Figure 2.9 shows the representation of the nonlinear reservoir model in SWMM. Each sub catchment is represented in SWMM as a nonlinear reservoir with a given slope (S) and width (W), and the resultant overland flow is estimated within each sub catchment.

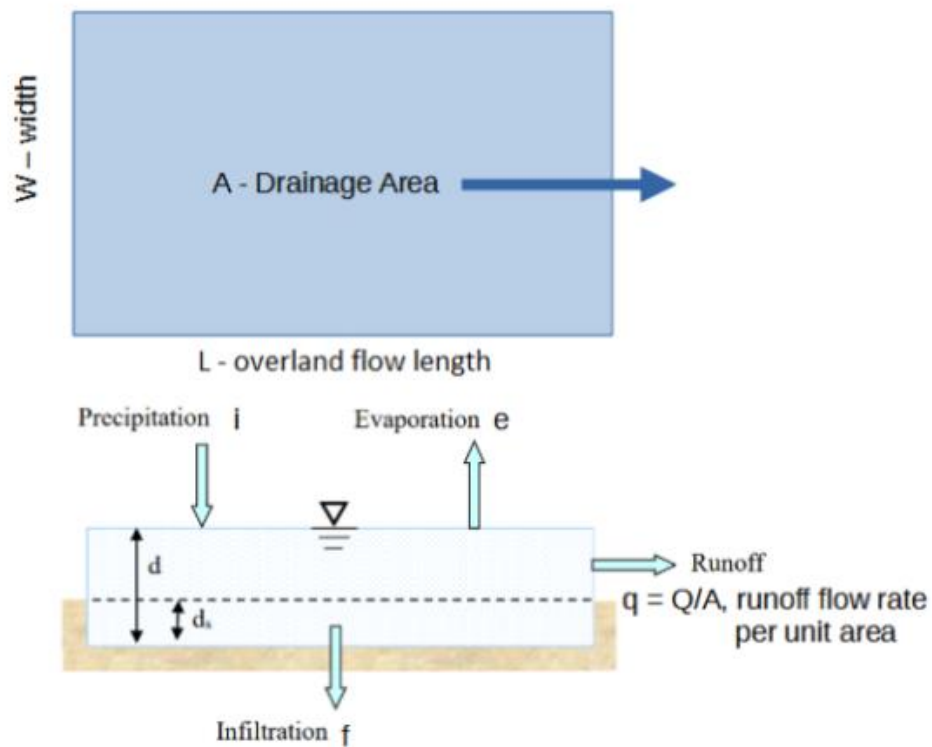


Figure 2.9. Nonlinear reservoir model [89]

The inputs and outputs of the runoff model in SWMM are shown in the above Figure. The input is precipitation, which includes both rainfall and snowmelt. The losses from the system are represented by evaporation and infiltration. The depth of net excess water that has accumulated on the sub catchment surface is indicated by the letter "d" in the diagram. The depression storage depth is indicated by the letter

" d_s ". Depression storage includes early rain abstractions including surface ponding, flat roof and vegetation interception, and surface wetting.

Many Hydraulic modeling tools use the unit hydrograph transform method to model the precipitation-runoff process, but the EPA SWMM has its own method called the nonlinear reservoir runoff method that treats a subcatchment as a shallow reservoir with its runoff flow being a nonlinear function of the reservoir's water depth by solving continuity equations (Figure 2.9). Since its release decades ago, several Hydraulic modeling products like XPSWMM and InfoWorks ICM have incorporated the SWMM nonlinear reservoir runoff method [90]. Continuity and Manning's equations in Equation 1 can be used to mathematically represent the nonlinear reservoir runoff approach, where i , e , and f are used to solve for d , q , and then $Q=q \times A$ at each time step. The drainage area A , overland flow Manning's n , depression storage d_s , width W , and subcatchment slope S , which should be measured along the overland flow path, are the parameters needed to carry out the nonlinear reservoir runoff method.

$$\frac{\partial d}{\partial t} = i - e - f - \alpha(d - d_s)^{5/3} \quad (1)$$

where,

$$\alpha = \frac{1.49WS^{\frac{1}{2}}}{A * n}$$

and

$$q = \frac{1.49WS^{\frac{1}{2}}}{A * n} (d - d_s)^{5/3}$$

As can be seen from the equations, the nonlinear reservoir runoff approach does away with the requirement to estimate the subjective and occasionally arbitrary Time of Concentration (TOC), but at the cost of predicting the subcatchment characteristic width W .

2.5 Rainfall-Runoff Methods

In order to design an appropriate Storm water management system, it is necessary to calculate the rainfall runoff. There are various methods available to determine the runoff. When it rains, some of the water is caught by vegetation, some seeps into the ground, and some evaporates before it gets there. The leftover water runs off the surface. Abstractions are these reductions in the quantity of rainwater that do not affect discharge. Interception, surface depression storage (puddles), evaporation, transpiration (water loss from plants), and infiltration are a few examples of abstractions. Unless there are considerable vegetative areas, evaporation and transpiration in urban environments are typically regarded as minimal for design-storm circumstances. Subtracting the abstraction from the total rainfall yields the excess or effective rainfall in urban areas. The overall amount of rainfall excess equals the total amount of runoff, and the rate of rainfall excess corresponds to the depth of runoff per unit of time [89]. Interception and penetration are the two main abstraction techniques in cities. The quantity of rainwater that plants holds in reserve before it seeps into the ground and evaporates into the atmosphere is referred to as "interception storage." When the plants' maximum storage capacity is reached, this process, which starts at the beginning of rainfall episodes, no longer has an impact on runoff. The kind, density, and volume of precipitation all affect how much interception occurs. However, interception losses for specific severe rainfall events can be taken as insignificant.

On the other hand, infiltration refers to the process through which precipitation enters the soil pores through the ground surface. A sizable fraction of the abstractions during a rainstorm event are caused by this process. Surface factors affect water availability, while sub-surface qualities have an impact on water infiltration. Surface and sub-surface conditions both have an impact on infiltration. The infiltration capacity is the greatest rate at which water can permeate. The infiltration rate is equal to the rainfall rate if the rainfall rate is less than the infiltration capacity [90].

Rainwater that collects in puddles on the ground and is prevented from evaporating with runoff is referred to as depression storage. Whether this water contacts impervious or pervious layers will affect how it behaves. Water evaporates on impervious layers while it soaks into pervious layers until saturation is attained before evaporating into the atmosphere. Although modeling depression storage might be challenging, it is frequently ignored since it is typically seen as insignificant in comparison to other methods of water abstraction [90]. The usual depression storage values for each land type are provided in Table 2.1 below.

Table 2.1. Typical depression storage values categorized by land cover [88]

Land Type	Storage (Inches)
Pasture	0.20
Lawns	0.10-0.20
Forest Litter	0.30
Impervious Surfaces	0.05-0.10

Various methods are employed in engineering to determine the abstractions of rainwater for rainfall-runoff calculations. These methods differ in the parameters necessary for estimating the runoff.

A straightforward technique for calculating rainfall runoff is the Φ -index model. It makes use of recorded rainfall-runoff data to calculate the Φ -index, which assumes a constant infiltration capacity. Rainfall that falls below the Φ -index value is thought to be lost by infiltration, while rainfall that falls above the Φ -index value is thought to be runoff [90].

The algebraic Green and Ampt model is a tool for calculating infiltration. It makes use of physical factors that are generated from the land usage and soil texture. The model takes into account a rain event on a permeable surface with a homogeneous initial saturation level. The amount of saturation rises when rain penetrates the

surface, although the increase is highest close to the surface and gets smaller as it goes deeper. The model assumes the existence of two zones: the saturated zone closer to the surface and the dry zone beneath the wetting front. These two zones are divided by a wetting front. As rainwater permeates the soil, the infiltration capacity falls, being higher in dry soil or below the wetting front.

The Horton approach uses experimental data to describe the infiltration capacity using an exponential decay curve. It takes into account variables including beginning and final penetration rates, duration of rainfall, and an exponential decay constant. These parameters can be found by fitting the equation to measured infiltration data. The current example will make use of the Horton model. The following parameters are necessary for the model:

- **Maximum infiltration rate:** This refers to the initial infiltration rate observed at the start of a storm. Estimating this rate can be challenging due to its dependence on the soil's moisture conditions before the storm. For dry soils, the values typically range from 1 in/h for clays to 5 in/h for sands.
- **Minimum infiltration rate:** This represents the limiting infiltration rate reached by the soil when it becomes fully saturated. It is commonly set equal to the soil's saturated hydraulic conductivity, which varies greatly depending on the soil type, ranging from 0.01 in/hr for clays to 4.7 in/hr for sand.
- **Decay coefficient:** This parameter determines the rate at which the infiltration rate declines from its initial maximum value to the minimum value. Typical values for the decay coefficient range from 2 to 7 hr⁻¹.

The Table 2.2 shows the values used for initial, final infiltration along with decay constant for different soil types.

Table 2.2. Hortons Parameters for Bluegrass Turf [88]

Soil type	Initial Infiltration (in./hr)	Final Infiltration (in./hr)	Decay constant (1/hr)
Silt loam, loam	8.0	0.50	2
Sandy, Loamy sand, Sandy loam	10.0	1.00	2
Sandy clay loam	5.0	0.25	2
Clay loam, Silty clay loam, Sandy clay, silty clay, clay	3.0	0.10	2

However, the Horton method has a limitation in that it only considers time and does not account for infiltrated water. If the rainfall rate is lower than the infiltration capacity between time 0 and t, the Horton method may underestimate the infiltration capacity. To address this, Akan (1992) [90] modified the Horton method by including the water infiltrated, resulting in the Modified Horton method.

The Horton technique is predicated on the idea that infiltration capacity is inversely related to soil moisture-holding capacity. The holding capacity of the soil diminishes when water infiltrates, which causes a corresponding decline in the infiltration capacity. Although this technique was initially created for agricultural areas, it can also be used in metropolitan areas with wooded and grassy areas.

The runoff curve number method, sometimes referred to as the Soil Conservation Service method (SCS), is a method for calculating rainfall runoff that takes into account a variety of variables, including interception, depression storage, evaporation, and infiltration. The soil in the study region is divided into four groups (A, B, C, and D) depending on its permeability in order to apply this procedure, as given below In the Table 2.3

Table 2.3. Soil textures corresponding to Hydrologic Soil Groups [90]

Hydrologic Soil Group	Soil Textures
A	Sand, Loamy Sand, Sandy Loam
B	Silt Loam or Loam
C	Sandy Clay Loam
D	Clay Loam, Silty Clay Loam, Sandy Clay or Clay

Sand, loamy sand, and sandy loam are examples of soil textures in Group A, while silt loam and loam textures are found in Group B. Group C includes sandy clay loam, while group D includes clay loam, silty clay loam, sandy loam, silty clay, and clay. While group B soils have moderate infiltration rates, group A soils have minimal potential for runoff and high infiltration rates. Group D soils have the largest potential for runoff among the four soil groups, whereas group C soils have poor infiltration rates and high potential for runoff [90]. The hydrologic soil group, soil cover type, land conditions, proportion of impermeable regions, and soil moisture level are some of the variables that affect the runoff curve number (CN), a parameter allocated to a basin that ranges from 0 to 100. The CN value is determined by these variables, as displayed in Table 2.4. To get a composite CN for the entire area when a sub-catchment has a different CN, a weighted average should be computed.

Table 2.4. Runoff Curve numbers for Urban land uses [93]

Cover description		Curve numbers for hydrologic soil group			
Cover type and hydrologic condition	Average percent impervious area	A	B	C	D
Fully developed urban areas (vegetation established)					
Open space (lawns, parks, golf courses, cemeteries, etc.)					
Poor condition (grass cover < 50%)		68	79	86	89
Fair condition (grass cover 50% to 75%)		49	69	79	84
Good condition (grass cover >75%)		39	61	74	80
Impervious areas					
Paved parking lots, roofs, driveways, etc. (excluding right-of-way)		98	98	98	98
Streets and roads					
Paved; curbs and storm sewers (excluding right-of-way)		98	98	98	98
Paved; open ditches (including right-of-way)		83	89	92	93
Gravel (including right-of-way)		76	85	89	91
Dirt (including right-of-way)		72	82	87	89
Western desert urban areas					
Natural desert landscaping (pervious areas only)		63	77	85	88
Artificial desert landscaping (impervious weed barrier, desert shrub with 1 to 2 inch sand or gravel mulch and basin borders)		96	96	96	96
Urban districts					
Commercial and business	85	89	92	94	95
Industrial	72	81	88	91	93
Residential districts by average lot size					
1/8 acre or less (town houses)	65	77	85	90	92
1/4 acre	38	61	75	83	87
1/3 acre	30	57	72	81	86
1/2 acre	25	54	70	80	85
1 acre	20	51	98	79	84
2 acres	12	46	65	77	82

2.6 Sustainable Stormwater Management and Life Cycle Assessment

The effectiveness of LIDs in treating storm water has been demonstrated, however their construction, installation, operation, maintenance, and disposal on the environment are not always taken into account [94]. A tool that can be used to

quantify these effects is life cycle assessment (LCA), but current LCA databases lack data on green infrastructures, and assumptions are frequently needed to get findings. LIDs, however, have better environmental effects than conventional infrastructure, according to a small body of studies [95].

The methodology used in this study follows the methodology set forth for life cycle, in this study, numerous types of LID techniques were implemented in various basins. Permeable pavement systems (PPS) were used on parking lots and walking paths, while bio-retention basins were created in permeable areas near roads and buildings to capture stormwater.

For large buildings where these options were not feasible, we employed roof RWHS. A simulated rainfall event of 22 mm/hr. was evaluated using the Software which is Storm Water Management Model (SWMM), and the results were recorded before and after the LID implementation. The results were analyzed in terms of total runoff from each basin, peak discharges, and pollutant buildup. The differences between before and after results were noted and compared. A LCA was also conducted to evaluate the environmental impact of the LID techniques.

This study uses the LCA approach as per ISO 14000 guidelines, which were developed by the International Standards Organization (ISO). ISO 14040 and 14044 present a structured approach for conducting Life Cycle Assessment (LCA), which consists of four stages: aim and scope definition, Life Cycle Inventory (LCI) analysis, Life Cycle Impact Assessment (LCIA), and interpretation. The structure and stages of LCA are depicted in Figure 2.10.

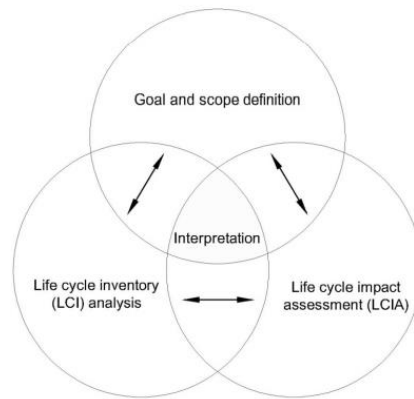


Figure 2.10. Life cycle assessment framework

In this reserach, an LCA was performed to assess and compare the environmental impacts associated with various types of LID measures. The LCA examined the materials and energy consumption throughout the life cycle of the LIDs by utilizing multiple databases for analysis, such as AGRIBALYSE 3.1, NEEDS, ELCD, and ecoinvent 3.7. The TRACI 2.1 impact assessment approach was then used to evaluate the impacts of the LIDs on 10 different midpoint categories, such as climate change and human health. This allowed for a comprehensive assessment of the environmental costs associated with different LID measures. Including the above, a comparative analysis will be done to understand the environmental impact and economic viability of Traditional Stormwater management over the Low Impact Development strategies. This study is being conducted in the hope that it will encourage a comprehensive and interdisciplinary understanding of LID systems and move decision-making for LIDs toward a greener approach.

CHAPTER 3

DESCRIPTION OF STUDY AREA

Two distinct research areas have been considered in this research one is Middle East Technical University Northern Cyprus Campus (METU-NCC) and another is Güzelyurt Town, both are located on the island of Cyprus, the description of each of them is discussed in the further sections.

3.1 Overview of METU-NCC

As seen in Figure 3.1, METU-NCC is located in the western portion of Northern Cyprus, roughly 50 km west of Lefkosa (Nicosia) and 6 km north of Güzelyurt.



Figure 3.1. Map of Cyprus [94]

The campus has a 339 hectare footprint and can house about 2500 people, including employees and students [103]. The top perspective of the entire campus is depicted in Figure 3.2.



Figure 3.2. METU-NCC Campus top view [103]

With the growing campus population each year, there is a corresponding increase in energy and water consumption. The university currently draws water from three wells in Güzelyurt for both potable and non-potable uses like irrigation, toilet flushing, washing, and cooking. This water is kept in a 4000 m³ concrete reservoir close to the EBI Dormitory structure. Since the university controls the wells, pumping expenses are the main cost associated with providing water for the campus. Due to irrigation using up about 90% of the water supplies, Cyprus confronts development challenges due to the island's severe water shortage. The aquifer has become contaminated as a result of over-pumping from wells that has exceeded the safe yield capacity of the aquifer [103]. The Güzelyurt aquifer is particularly affected by this issue [103], and the water quality in the Güzelyurt Basin has deteriorated due to saltwater intrusion. The excessive groundwater pumping has caused the groundwater table to decline, exacerbating saltwater intrusion. Additionally, groundwater pollution occurs due to industrial contamination, ore bed pollution, and the discharge of waste into water resource reception basins and the sea. Consequently, both the quantity and quality of

groundwater are negatively impacted. It is anticipated that reducing groundwater pumping, coupled with the water transfer project from Turkey, will have a positive effect on the situation.

3.2 Overview of Güzelyurt Town

Güzelyurt, situated in Northern Cyprus, is the fourth largest city following Nicosia, Famagusta, and Kyrenia. Its geographical coordinates are approximately 32° 59' longitude and 35° 12'N latitude. According to the 2011 population census, Güzelyurt had a population of 30,037, accounting for approximately 10.4% of the total population in Northern Cyprus at that time [98]. Lefke and Güzelyurt central are the two principal districts that make up the region. According to the 2011 census, Güzelyurt central has 18,946 residents, or 6.6% of the total population. Figure 3.3 provides more demographic information.

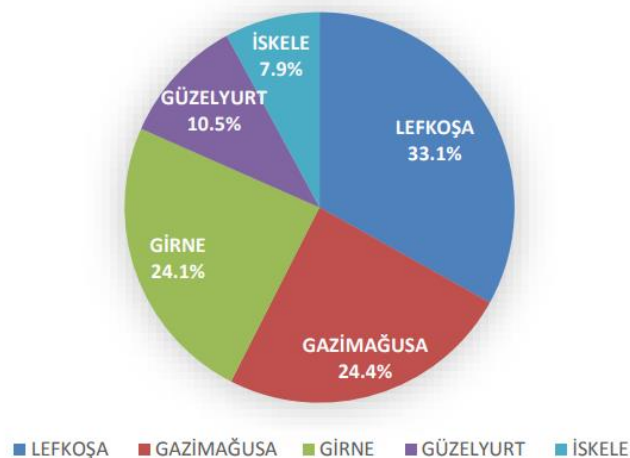


Figure 3.3. Demographics of Northern Cyprus [98].

It is worth noting that the population of Güzelyurt experienced a growth of 2.6%, rising from 29,264 in 2006 to 30,037 in 2011 [98]. Güzelyurt Town is situated in the northwestern part of Cyprus, approximately 40 km west of Nicosia and about 7 km away from the coastline. Figure 3.4 provides an illustration of the study area's location at different scales.

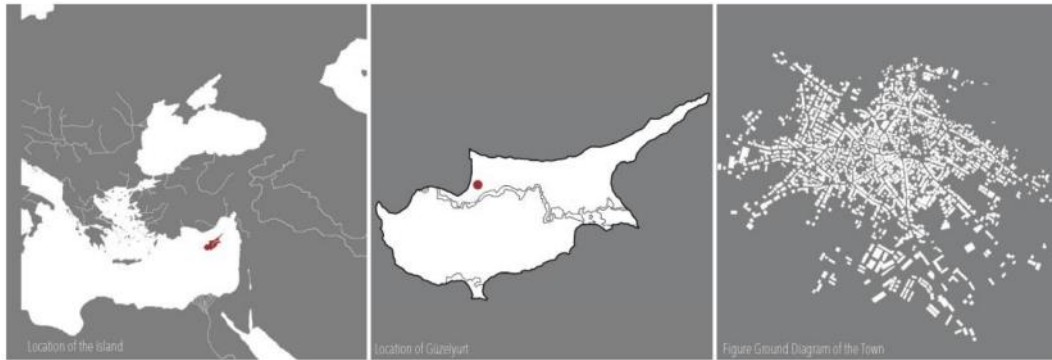


Figure 3.4. Location of Study area in various Scales [100]

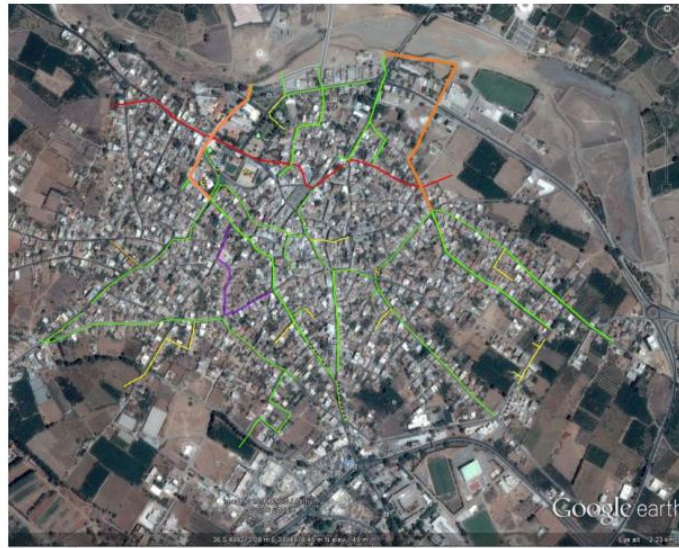
The total area of Güzelyurt is reported to be 381 square kilometers, with the urbanized portion encompassing approximately 3-4 square kilometers. Fruit orchards and agricultural terrain surround the urban area. The terrain in the area is typically level and slopes steadily toward the river bed on the town's northern edge. The Serrahi river bank is dry, the construction of three dams upstream, removing the possibility of floods in the Güzelyurt urban region. Moreover, directly beneath the town lies the largest water table in Northern Cyprus, which serves as a significant water resource for the region. Given the absence of permanent rivers in the area, 92% of water consumption relies on aquifers, resulting in a significant decline in the groundwater levels, particularly in the Güzelyurt aquifer. This decline has led to the intrusion of seawater into the aquifer, causing an increase in salinity levels up to 5000 ppm [100].

Güzelyurt has a climate that can be described as Mediterranean and semi-arid. The summer months of June, July, and August are characterized by hot and dry conditions with minimal rainfall. The urban design of the town has remained largely unchanged since the 1970s due to uncertainties surrounding property ownership. Additionally, the relatively low cost of land in Güzelyurt has resulted in a high density of residential areas, with 67% of dwellings consisting of single-family detached houses, 20% being semi-detached or double-storey houses, and

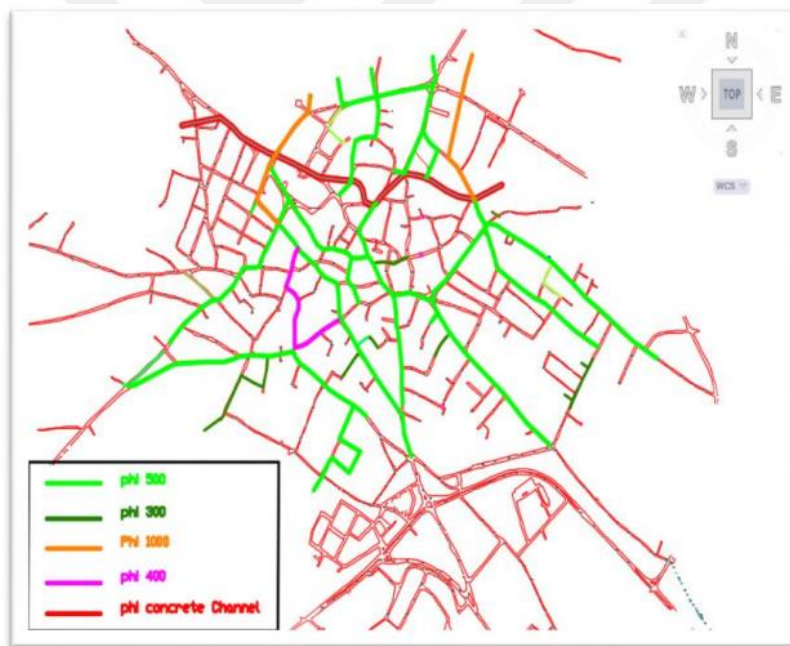
only 3% comprising apartment buildings. The remaining 6.7% of buildings consist of traced/row housing [99].

3.2.1 Existing Stormwater Network in Güzelyurt

The existing pipe system in the urban area is incomplete, as not all streets are covered by drainage infrastructure. As a result, streets without a drainage system rely on natural slopes to direct rainwater runoff towards the stormwater drain. This can lead to water accumulation and flooding at street junctions. Additionally, the stormwater network system has experienced failures even during regular rainfall events due to its insufficient capacity. The town has an outdated sewerage system, but no maps or comprehensive documents are readily available that explain the current pipe system, including profiles or cross-sections. The municipality was contacted to gather data on the pipe locations and sizes. After couple of meetings with the technical staff of Güzelyurt Municipality, all the existing pipes in the town, along with their sizes, were determined and recorded on a paper map [99]. Figure 3.5 (a) & (b) illustrates the locations of the pipes in the town, with each pipe's size indicated by different colors. The most common pipe size used for the drainage system, represented by green lines, is 500 mm in diameter. Purple lines indicate pipes with a diameter of 400 mm, while yellow lines represent pipes with a diameter of 300 mm. An orange line on the map indicates one-meter diameter pipes used to convey the entire runoff to the riverbed in the northern part of the town. Furthermore, there is an old concrete rectangular channel, depicted by a thick red line running from east to west, which was originally used for irrigating gardens on the west side of the town. However, with the current use of reservoirs on the east side, this channel is no longer utilized for irrigation purposes, except for a few meters where it is used to transfer water to another pipe system.



(a)



(b)

Figure 3.5. The piping network of Güzelyurt generated in Google Earth [99]

3.2.2 Slope conditions and Land use

The topography of Güzelyurt demonstrates a consistent slope from southeast to northwest, as depicted in Figure 3.6. Higher elevations are represented by dark blue color, while lower elevations are depicted in light blue. The figure clearly illustrates the uniform downward slope of the entire region towards the northwest direction.

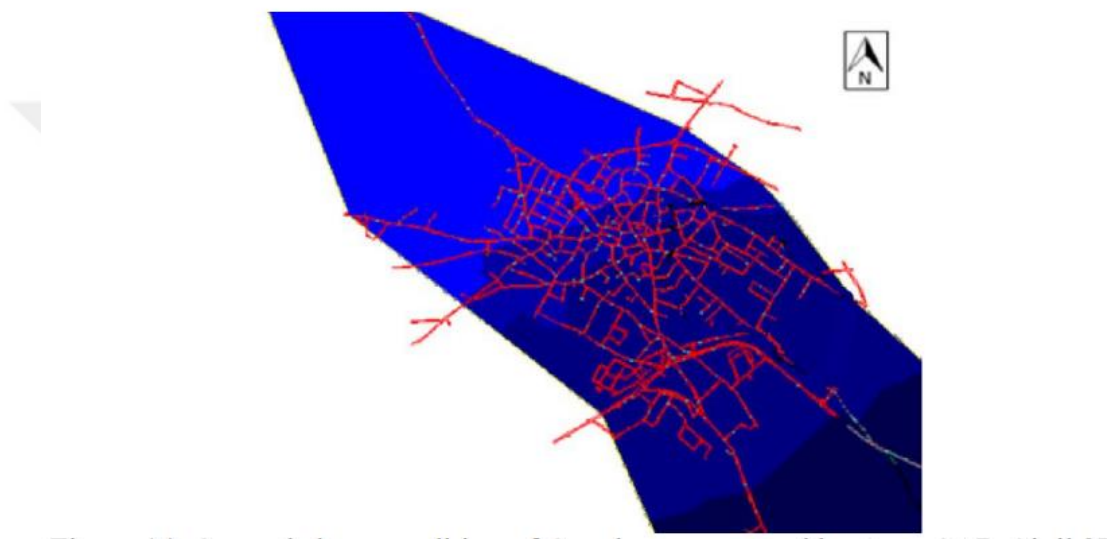


Figure 3.6. Slope conditions of Güzelyurt Town generated using Auto CAD Civil 3D Software [99]

Land use encompasses the human activities and interventions on the land to utilize its resources, as discussed by Niehoff [102]. These land use changes have direct impacts on the ecosystem, altering the water cycle, biodiversity, and radiation budget, as highlighted by Riebsame et al. [104]. The alteration of land use can significantly influence the infiltration conditions, soil microporosity, and dynamics of the saturated zone, thereby affecting the volume of runoff in various direct runoff models. Land use patterns are also flexible and influenced by management, social, and economic agendas. Understanding land usage and land cover is essential for planning a water supply, managing the existing water resources, and preventing flooding.

Three broad categories can be used to categorize land usage in Guzelyurt. First off, a sizeable amount of the metropolitan area is made up of impermeable surfaces including roofs, streets, pavements, and parking lots. Second, pervious surfaces such lawns, fields, bare lands, cultivated land, gardens, and forests make up the majority of the rural area. The third classification is a combination of rural and urban area called a semi-urban area.



CHAPTER 4

DATA AND METHODOLOGY

The subsequent sections in this chapter focus on acquiring the necessary data for the analysis and describing the methodology employed throughout the research.

4.1 Catchment Characteristics (METU-NCC)

An examination of the catchment characteristics of the campus is required to ascertain the amount of runoff there. Seven sub-catchments were discovered and defined by taking into account the change in elevation and the anticipated flow of rainwater runoff towards the drainage system's discharge ports. Each sub-catchment has a distinct surface make-up and discharge outlet. The software programs were utilized to calculate the areas of these sub-catchments like AutoCAD 2011 and Google Earth to delineate the sub-catchment areas and investigate various surfaces, coupled with a campus map that depicts the drainage network layout [103]. To estimate the amount of runoff, the area of each surface was also calculated. In Figure 4.1, the discovered sub-catchments are shown. The sub catchments were not only identified but also analyzed in terms of their characteristics, including the total area, impervious area, and pervious area. The identification of impervious and pervious areas was conducted by examining surface features such as rooftops, parking lots, and walking paths using Google Earth Pro software. Impervious areas were determined based on these features, while areas with lawns and other similar characteristics were classified as pervious areas. Table 4.1 presents the percentages of impervious and pervious area.

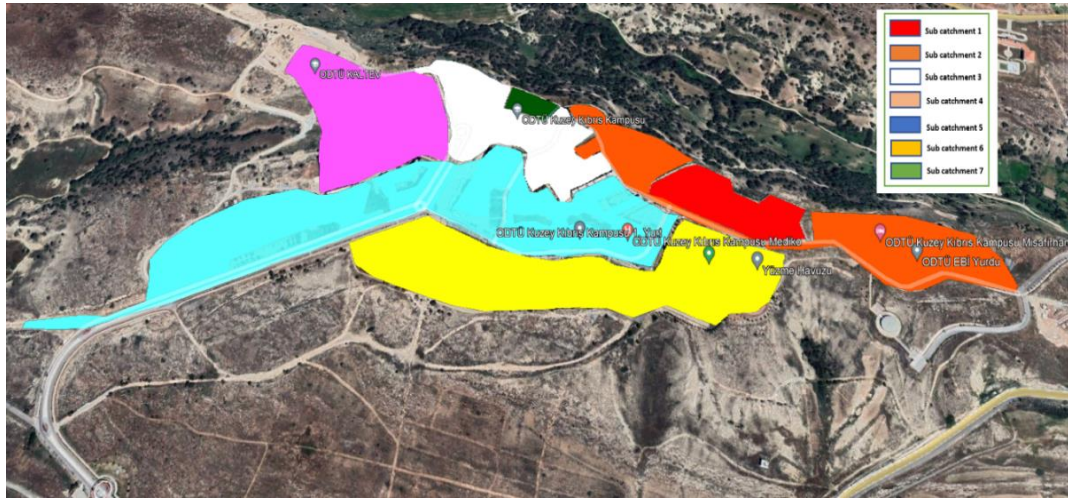


Figure 4.1. The METU-NCC Plan Incorporating various catchments [103]

Table 4.1. Basin Characteristics

Basin	Total area (m ²)	Impervious (%)	Pervious (%)
1	14888	71	29
2	44691	65	35
3	34570	64	36
4	48360	66	34
5	124462	58	42
6	73030	65	35
7	6971	83	17

It can be observed that the percentages of impervious areas (such as buildings and paved surfaces) are higher in all of the basins when compared to the pervious areas

(such as vegetation and soil). This implies that there is a high likelihood of runoff on the streets as a result of the increased concretization of the catchment area. This can cause increased runoff during heavy precipitation events, as the water is not able to permeate the ground and instead flows over the surface, increasing the likelihood of flooding. Furthermore, the high percentage of impervious surfaces in the catchment area means that the water that does run off carries' pollutants, negatively impacting the water quality at the discharge point.

4.2 Data Acquisition and Catchment Characterization (Güzelyurt Town)

According to Rossman [110], subcatchments are designated tracts of land that, while taking into consideration topography and drainage system architecture, enable the drainage of surface runoff towards a single discharge point. Watershed, catchment, or drainage basin are additional terms frequently used to represent the land area directing runoff toward a stormwater facility. To conduct a rainfall-runoff analysis and calculate the contribution of runoff to particular sites, subareas must be identified. The borders of subareas need to take a number of things into account. First off, precise plans of inlet locations are required because the position of inlets and the existing pipe system are vital in identifying subarea borders. Second, surface runoff flow directions must be evaluated because there is no piping infrastructure in each street, thus runoff flows over the top of the ground and into the nearest drain inlets. As a result, determining the flow directions along each roadway is crucial for drawing the boundaries of subareas. Additionally, the Google Earth Pro software gives users access to Google Earth aerial images, which provide a full view of the urban region and help identify subareas. Subsequent chapters will go into more detail about these criteria, which are important for defining subareas. Setting up catchments for each inlet in the pipe system is crucial in order to build a hydraulic model of the stormwater management system. The volume of runoff that impacts particular portions of the pipe system can be determined by specifying these catchments. It is not essential to create catchments

for each individual inlet in the current study because the space between inlets rarely exceeds 4 meters and never exceeds 14 meters. Based on the recommendations made by Akan and Houghtalen in 2003 [90], a maximum distance of 100 meters between manholes is assumed in this analysis to prevent needless redundancy in subcatchments. Pipe connections, differences in ground elevation, and other considerations can be used to estimate the minimum distance for designing manholes. Overland flow happens when the surface's capacity for infiltration and depression storage is saturated and the rate of rainfall exceeds the rate at which water is lost. As a result, a thin layer of water forms on the surface and is subsequently propelled downward by gravity down the steepest slope. The sharpest slope under various situations must be identified, and the associated flow direction must be established, in order to examine the direction of overland flow. The slopes and flow directions between each elevation point were manually computed using the accessible road map and elevation information provided by the municipality. In Figure 4.2, the flow directions are represented by black arrows. Although the direction of the arrows may not be discernible in the overall view.



Figure 4.2. Flow directions on the streets generated manually using the elevation difference [99]

4.2.1 Subcatchment classification

Once the subareas contributing to each manhole were identified and combined, four primary subcatchments were established, as depicted in Figure 4.3 and the characteristics are plotted in Table 4.2. Subcatchment A covers an area of 0.55 square kilometers, subcatchment B covers 0.15 square kilometers, subcatchment C covers 0.29 square kilometers, and subcatchment D covers 0.10 square kilometers approximately. The exit points for all subcatchments are situated near the dry riverbed of the Serahis river [99].

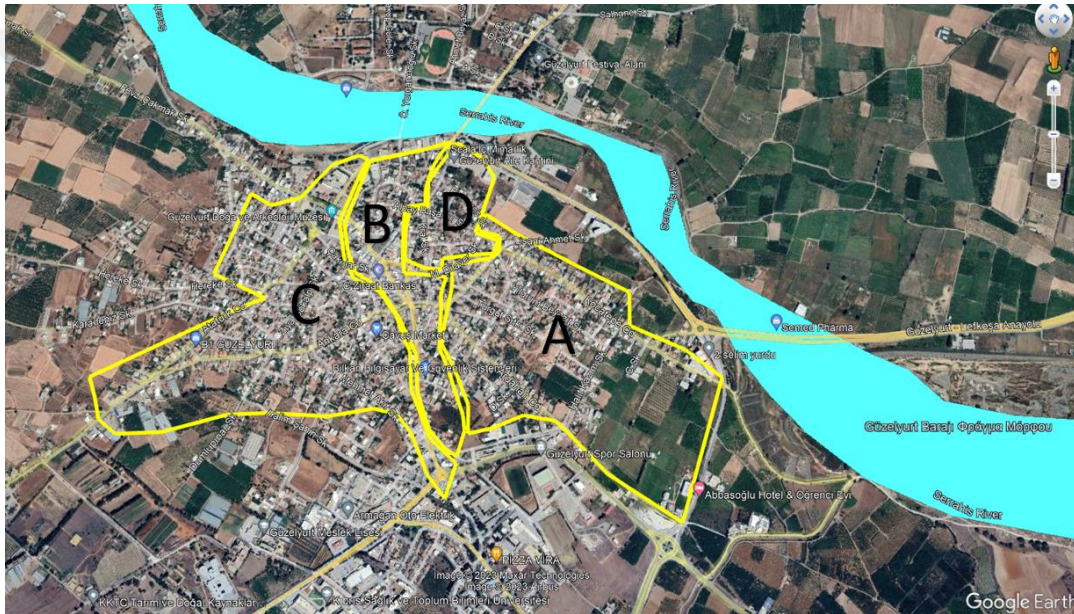


Figure 4.3. Sub-catchments of the Güzeyurt Town

Table 4.2. The charactersitics of the subctachments [99]

Sub catchments	Total Area (m ²)	Subareas	Impervious %
A	550373	35	27
B	149735	26	64
C	291375	60	62
D	79319	9	51

As shown in the Table 4.2, the highest imperviousness percentage is in Sub-catchment B, thus for this reserach the Sub-catchment B is considered for analysis.

4.3 Runoff Estimation

The Soil Conservation Service (SCS) approach is frequently used in stormwater design to estimate runoff volume from catchments and is useful since it takes into consideration different types of abstractions and the parameters required to compute the runoff. Other methods may require difficult-to-obtain data or significant experimental work, making them less suitable in some cases. The availability of data and the suitability of the method should be considered when choosing a method for calculating runoff. In this research area for METU-NCC, the SCS method can be used since applicable and necessary parameters are available. The surface's curve number (CN) is determined by the hydrologic soil group in the area, which is defined by soil texture and surface cover type [99]. In terms of hydrologic soil group, the soil in the campus area is most similar to soil Group D.

Equation 2 below should be used to multiply each individual region by its corresponding CN, add the results, then divide the sum by the sub-overall catchment's area to determine the CN of the sub-normalized catchment.

$$CN_N = \sum_{i=1}^n \left(\frac{A_i \times CN_i}{A_T} \right) \quad (2)$$

where, A_T is the total area of the sub-catchment (m^2); CN_N is the normalized CN of a sub-catchment; n is the total number of surfaces in the sub-catchment, A_i is the area of each surface in a sub-catchment (m^2); CN_i is the CN of each surface in the sub-catchment. After finding CN_N , the Equation 3 is used to find the soil moisture deficit

$$S_D = \frac{25400 - 254 \cdot CN_N}{CN_N} \quad (3)$$

where, S_D the soil moisture deficit at the onset of runoff is expressed in millimeters (mm); CN_N is the normalized runoff curve number.

The water that is intercepted by plants, held in surface depressions, evaporated, or pierced before the runoff begins makes up the initial abstraction, which is determined by equation 4. Additionally, the precipitation must surpass the initial abstraction for this equation to be applicable.

$$I_a = 0.2 S_D \quad (4)$$

where, S_D is the soil moisture deficit at the time of runoff (mm) and I_a is the initial abstraction (mm).

Finally, once all parameters have been calculated, the runoff may be calculated using the SCS runoff expression found in Equation 5.

$$R = \frac{(P - I_a)^2}{(P - I_a) + S_D} \quad (5)$$

where, P is the precipitation (mm); R is the rainfall runoff (mm); I_a is the initial abstraction (mm) and the S_D is the soil moisture deficit at the time of runoff (mm). Equation 6 is used to compute the volume of runoff from each sub-catchment once the runoff has been calculated.

$$V = R \times A_T \quad (6)$$

where, R is the rainfall runoff (m); V is the volume of runoff (m³) and A_T is the area of the sub-catchment (m²).

The Horton method was selected in the current study of Güzelyurt Town to determine the infiltration rate. This method is widely recognized and regarded as one of the most well-known infiltration equations [89]. In the Horton method, the infiltration begins at a maximum initial value and gradually decreases exponentially until it reaches the minimum infiltration rate. The decay coefficient determines how quickly the exponential curve flattens out. As seen in Figure 4.4, the infiltration capacity rises as the decay coefficient falls, slowing the rate of loss.

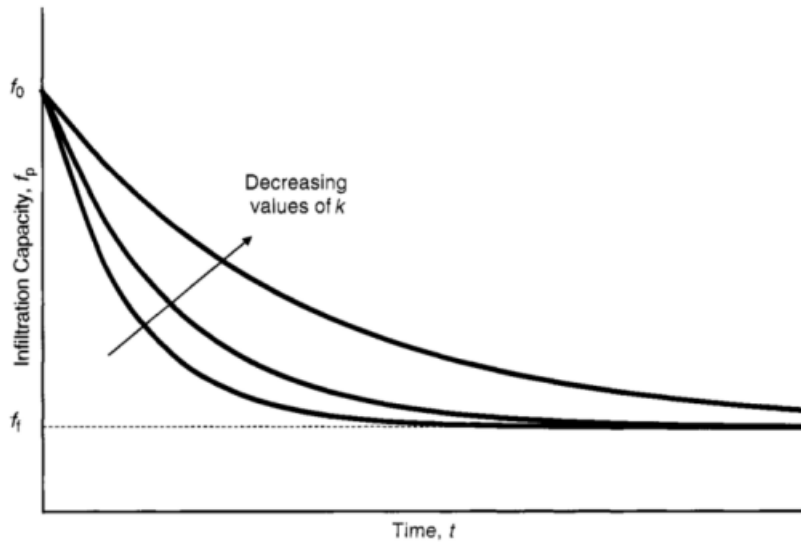


Figure 4.4. Horton Infiltration Capacity [90]

The exponential decay function proposed by Horton in 1940 is used as the equation for the Horton method and is provided below,

$$f_p = f_f + (f_0 - f_f)e^{-kt} \quad (7)$$

where:

f_p = Infiltration capacity

f_f = Final Infiltration capacity

f_0 = initial Infiltration capacity

k = exponential decay constant and

t = time from beginning of rainfall

The chosen method, Horton method, requires the determination of three parameters (f_0 , f_f , k) based on the soil type. In the studied region, the soil types are identified as sandy clay loam soil.

4.4 SWMM Modelling

The Environmental Protection Agency (EPA) developed SWMM, a program that models the quantity and quality of runoff from urban sub-catchment regions. Stormwater drainage network planning, design, and analysis are where it is most frequently employed. SWMM 5.2 provides a platform that is integrated for managing study area input data and running hydrologic, hydraulic, and water quality simulations. When calculating runoff in urban environments, it takes a number of hydrologic phenomena into account, including time-varying rainfall, evaporation, snow accumulation and melting, and infiltration. It also has a number of hydraulic modeling tools that can be used to direct runoff and outside inflows through the transportation networks. SWMM can also be used to assess the buildup of pollutant loads related to runoff [89]. The SWMM software utilizes three infiltration methods, namely Horton, Green Ampt, and SCS Curve Number, to simulate the process of rainfall infiltration into the unsaturated topsoil zone within a sub-catchment.

The SWMM program was selected due to its wide acceptability, availability for free download, and comprehensive output. It is a physically based, deterministic model that simulates the interaction between precipitation and runoff. It is also capable of simulating hydrologic processes like infiltration and overland flow while routing runoff through a drainage system made up of pipes, channels, storage/treatment equipment, pumps, and regulators. The Land Uses should be adjusted to model pollution buildup and wash-off, and the Snow Pack object should be utilized to simulate snow melting or accumulation. The specified rain gage, outlet node, land uses, imperviousness layer percentage, sub-catchment slope, width of overland flow, Manning's n for both the pervious and impervious sections, and depression storage in the pervious and impervious areas are input characteristics utilized in the sub-catchment object. The length units for this study are meters, the rainfall depth units are millimeters, the sub-catchment area units are hectares, and the runoff volume units are liters. For this research, Horton and the

SCS technique were chosen, and steady flow was the default routing method. A screenshot depicting the campus layout from Google Earth was used to match the areas to be created on SWMM. The SWMM model was used to map sub-catchments, including area, impervious layer percentage, slope, and channel width. Rainwater was assumed to be 100% routed, with rainfall data from a designated gauge. Soil characteristics and outfall nodes were added for each sub-catchment. Hydraulic conductivity was not included.

The SWMM model was chosen for its widespread use and ability to simulate a dynamic rainfall-runoff model for urban sub-catchment areas. It takes into account various types of abstractions like infiltration and evaporation. Sub-catchments were drawn on the map, and the total area, percentage of impervious layers, percentage of slope, and width of overland flow channel were added. Parameters were entered and the simulation was run using the SCS approach and Horton method for Güzelyurt town. The results were analyzed in terms of total runoff, peak discharges, and pollutant buildup. Rainfall data was added using the Rain Gage tab and the simulation start and end dates were chosen from the Dates tab under the Options tab.

4.4.1 Conceptual Elements of SWMM Modelling

Rain Gages

Time series are used to show how particular values change over time. Different time series, such as temperature data, evaporation data, and precipitation data, can be defined in SWMM. In simulations of rainfall-runoff, precipitation is a critical factor. A time series can include a single event with a small number of time steps or a long-term event with a large number of time steps, imitating a multiyear model. Precipitation series are specified within the Rain Gage object, which is symbolized by an icon, in the SWMM model. To accurately capture the regional variability of precipitation, many rain gauges might be created. Time series

definitions can be made manually by the user or with the use of file data. Daily average precipitations are not appropriate because SWMM time steps are often on the order of minutes or fewer. In this study, a created rainfall pattern was adopted because high-resolution observed rainfall data for Güzelyurtand METU-NCC were not available. A one-hour period of uniformly arranged rainfall with varied intensities was used. To test the rainfall data's response, several intensities were applied. It is crucial to check that the time interval in the series matches the interval in the rain gauge when defining time series. If not, each value in the time series will be connected to the corresponding intervals of time that the rain gauge specifies.

Sub-catchments

In SWMM, subcatchments are visually represented as hatched parcels and are composed of both pervious and impervious areas with varying ratios determined by the percentage of imperviousness. The impervious areas can further be categorized into two subtypes: those without depression storage and those with depression storage. All subareas within the subcatchments are directly connected to the outlet. When defining the characteristics of a subcatchment in SWMM, the following parameters need to be specified:

- Manning coefficient for pervious and impervious areas
- Depression storage for pervious and impervious areas
- Subcatchment slope
- Imperviousness
- Infiltration method
- Impervious area without depression storage
- Characteristic width of overland flow
- Subcatchment area

As shown in Figure 4.5, these characteristics are essential for effectively modeling and simulating the behavior of the subcatchments in the SWMM program.

Subcatchment B1-1	
Property	Value
Name	B1-1
X-Coordinate	9545.454
Y-Coordinate	529.344
Description	
Tag	
Rain Gage	RG1
Outlet	J1
Area	1.51
Width	138.48
% Slope	1.1
% Imperv	15
N-Imperv	0.040
N-Perv	0.056
Dstore-Imperv	1.6
Dstore-Perv	6.4
%Zero-Imperv	0
Subarea Routing	OUTLET
Percent Routed	100
Infiltration Data	HORTON
Groundwater	NO
Snow Pack	
LID Controls	0
Land Uses	0
Initial Buildup	NONE
Curb Length	0
N-Perv Pattern	
Dstore Pattern	
Infil. Pattern	
User-assigned name of subcatchment	

Figure 4.5. Sub-catchments data window in SWMM Software

Imperviousness

Accurately estimating the impervious area is crucial for determining runoff characteristics, as this parameter has a significant impact. A recommended approach to estimate the impervious area involves utilizing aerial photos in conjunction with topographic maps. In this study, aerial photos from Google Earth were employed to identify and quantify impervious surfaces within each subcatchment. The amount of impervious surfaces can be calculated by identifying specific elements in the Google Earth aerial photographs, such as roof tops, streets, and parking lots. The SWMM software requires the percentage of imperviousness as an input.

Width of Overland Flow

Determining the width of subcatchments can be approached using various methods, considering that not all subcatchments have a symmetrical rectangular shape. The width parameter is of significant importance in modeling, as it directly influences the shape of the hydrograph. For instance, a bigger subcatchment will reach its maximum outflow more quickly at the outlet point than a narrower subcatchment, which will result in a delayed period of maximum outflow. Various possibilities could happen depending on how the subcatchments are shaped. The breadth will be twice as wide as the main drainage channel if the subcatchment has a major drainage channel in the middle of a rectangular shape. The breadth will be the same as the length of the channel if the main channel is situated on the side of the subcatchment. Equation (8), as a modification of this method to take into account more irregular subcatchments. In the equation, L stands for the length of the main drainage channel, and Z stands for the proportion of the subcatchment's total area (A) to the bigger area (A_m) on the channel's side. Z represents the subcatchment's skewness from a symmetric condition.

$$W = L + 2L(1 - Z) \quad (8)$$

$$Z = A_m/A$$

Where: Z = skew factor, $0.5 < Z < 1$

A_m = Larger of the two areas on each side of the channel.

A =Total area

L = Length of the main drainage channel

Slopes

The slope of the subcatchment represents the average incline of overland flow towards the inlet location. Accurate slope estimation is more feasible when the subcatchment shape is relatively simple. In developed catchments, it is preferable to construct slopes that facilitate uniform flow conveyance over the ground. However, practical constraints often prevent this ideal scenario, leading to irregularities. In such cases, the method of area-weighted average can be employed to address the irregularity. In metropolitan settings, overland flow mainly happens along streets and roads, which act as routes to the primary drainage system. As a result, each subcatchment's roadway slopes are computed in accordance with the advice given in the literature [91].

Manning Coefficient for Overland and Conduits

The roughness or resistance to flow within a channel or pipe is described by the Manning coefficient, often known as Manning's roughness coefficient or Manning's n , a parameter used in open channel flow computations. It depicts the frictional impacts between the channel's edge and the flowing water. The characteristics of the channel, such as its surface roughness, vegetation, obstacles, and other elements that affect flow resistance, are often used to determine the Manning coefficient's value. It is used to calculate flow rates, water surface profiles, and hydraulic gradients in open channels in a variety of hydraulic models and equations, including the Manning's equation. The Manning coefficient is different for different type of land uses and also different for the types of pipes used in the drainage network, the Table 4.3 and Table 4.4 depicts the Manning's coefficient for different scenarios. In the case of conduits, which are the drainage pipes used in the study areas, the Manning coefficient is used to describe the roughness or resistance to flow inside the pipes. The material and smoothness of the pipes play a significant role in determining the appropriate Manning coefficient. In the METU NCC area, the drainage pipes are made of smooth asphalt, while in the Güzelyurt Townarea,

the pipes are made of smooth concrete. The corresponding Manning coefficients for these conduits can be found in Table 4.3. and Table 4.4. below. These tables provide the specific values of the Manning coefficient that were obtained for the different flow conditions and conduit materials in the study areas. These coefficients are crucial in accurately estimating flow velocities, water surface profiles, and hydraulic gradients within the drainage systems

Table 4.3. Mannings coefficient for Overland flow [88]

Surface	n
Smooth asphalt	0.011
Smooth concrete	0.012
Ordinary concrete lining	0.013
Good wood	0.014
Brick with cement mortar	0.014
Vitrified clay	0.015
Cast iron	0.015
Corrugated metal pipes	0.024
Cement rubble surface	0.024
Fallow soils (no residue)	0.05
Cultivated soils	
Residue cover < 20%	0.06
Residue cover > 20%	0.17
Range (natural)	0.13
Grass	
Short, prairie	0.15
Dense	0.24
Bermuda grass	0.41
Woods	
Light underbrush	0.40
Dense underbrush	0.80

Table 4.4. Mannings coefficient for closed conduits [88]

Conduit Material	Manning n
Asbestos-cement pipe	0.011 - 0.015
Brick	0.013 - 0.017
Cast iron pipe - Cement-lined & seal coated	0.011 - 0.015
Concrete (monolithic) - Smooth forms - Rough forms	0.012 - 0.014 0.015 - 0.017
Concrete pipe	0.011 - 0.015
Corrugated-metal pipe (1/2-in. x 2-2/3-in. corrugations) - Plain - Paved invert - Spun asphalt lined	0.022 - 0.026 0.018 - 0.022 0.011 - 0.015
Plastic pipe (smooth)	0.011 - 0.015
Vitrified clay - Pipes - Liner plates	0.011 - 0.015 0.013 - 0.017

Depression Storage

Depression storage, often referred to as retention storage, is the volume of precipitation that must slough off impermeable and pervious surfaces before it can become runoff. This first storage, which is seen as a loss, is frequently brought on by elements such surface wetting, ponding, interception, and evaporation. Soil type, land usage, and slope are only a few of the variables that have an impact on the depression storage volume. Depression storage in pervious environments is directly related to how different vegetation types intercept water and the stage of that vegetation's development. Estimations for depression storage in relation to various vegetation types have been reported in literature. For this particular study, a depression storage value of 6.4 mm is assumed for pervious areas and 1.6 mm for impervious areas, as suggested by literature [90] and in close agreement with

values reported by the American Society of Civil Engineering for the Güzelyurt Town. For METU-NCC the depression storage for both pervious and impervious areas are considered to be 0.05 [103].

Junction Nodes

Junctions play a crucial role in hydraulic system modeling as they represent manholes or access chambers within the sewerage system. These structures are designed to facilitate easy access for maintenance and inspections. Additionally, they serve the purpose of providing ventilation to the sewerage system. Manholes are specifically designed for situations where two or more pipes intersect, there is a change in pipe sizes, or adjustments in alignment or grade are required. In long and straight sections of the system, it is recommended to incorporate manholes approximately every 100 meters to simplify maintenance operations [91]. Three crucial factors must be established before junctions can be defined in the SWMM model. The lowest elevation of the manhole construction, known as the invert elevation of the connection, is first determined. This is obtained by deducting the depth of the excavation and the pipe from the elevation of the ground.

The distance between the invert and the ground surface is represented by the second parameter, the maximum water depth. By changing this parameter, you can raise the water level to the top of the earth. The water level can also rise to the highest connecting link's top if this value is set to zero. The ponded area, which in this case refers to the surface area that undergoes ponding when the water level exceeds the limit water depth, is the final metric. When employing dynamic wave modeling approaches, this parameter is especially crucial. The ponded area is set to zero in this study because the model is based on kinematic wave routing. The junction parameters and their configurations inside the model are shown visually in Figure 4.6, which depicts a junction data window in the SWMM software.

Property	Value
Name	J1
X-Coordinate	7658.228
Y-Coordinate	506.329
Description	
Tag	
Inflows	NO
Treatment	NO
Invert El.	48.532
Max. Depth	0.8
Initial Depth	0
Surcharge Depth	0
Ponded Area	0
User-assigned name of junction	

Figure 4.6. Junction Data Information in SWMM Software

Conduits

There are two basic categories included in SWMM's hydraulic modeling of the system: nodes and linkages. The link section includes a number of parts, including outlets, conduits, pumps, orifices, and weirs. Conduits are a key component of the hydraulic system modeling in this particular case study. Lines connecting two nodes, which are analogous to manholes in a real stormwater management system, serve as conduits. To define conduits in the model, several key parameters need to be specified. These include the inlet node, outlet node, conduit shape, diameter (or maximum depth for rectangular conduits), length, and pipe roughness. The system's conduit connection points are determined by the choice of the input and

outflow nodes. The conduits can be made in a variety of designs; circular conduits just need to meet the pipe's diameter requirements while rectangular conduits also need to meet depth and bottom width requirements. The map or other resources are good places to look up the pipe's length. The pipe's roughness coefficient must also be established using its features. For the drainage system in this case study, two different pipe materials are used: cement pipe for the METU-NCC research area and concrete pipe for Güzelyurt Town. The Table 8 provides the manning coefficient for various pipelines, which will influence the selection of the roughness coefficient. By defining these parameters accurately, the conduits in the SWMM model facilitate the simulation and analysis of the hydraulic behavior within the stormwater management system. Figure 4.7. shows the conduit option in SWMM,

4.5 Low Impact Development Strategies Application

Low Impact Developments (LID) encompass a range of strategies aimed at mitigating the adverse effects of urbanization by reducing the runoff generated from impervious surfaces. These practices involve the implementation of various techniques that promote increased infiltration and evapotranspiration.

Within the SWMM program, it is feasible to simulate various Sustainable Stormwater Management applications, including Gardens, Green Roofs, Infiltration Trenches, Permeable Pavement, Rooftop Disconnections, Vegetative Swales, and Rain Barrels.

Property	Value
Name	C1
Inlet Node	J1
Outlet Node	J2
Description	
Tag	
Shape	CIRCULAR
Max. Depth	.5
Length	53.25
Roughness	0.010
Optional category or classification	

Figure 4.7. Conduit properties in SWMM

The implementation of LID solutions helps to reduce the harm that urbanization and development have on the environment. By imitating the natural water cycle, these solutions seek to control storm water and lessen the load on drainage and sewage systems. The utilization of rain gardens, green roofs, bio-retention basins, permeable pavements, and the rainwater harvesting systems are just a few of the approaches used in LID plans. By allowing the water to penetrate into the ground as it would naturally, the major goal of employing LID techniques is to control storm water runoff at its source. As a result, there will be less runoff and less chance of floods, both of which can harm both people and their property. LID tactics also contribute to better water quality by filtering pollutants before they reach surface waters by enabling water to permeate the ground.

In the reserach area of METU-NCC, the dataset of general characteristics such as types of land surfaces, areas, the CN number for different land areas are all derived from a previous reserach conducted for METU-NCC [103]. The characteristics are mentioned in the Table 4.5.

Table 4.5. The Input data for SWMM model for Sub-catchments for METU-NCC [103]

Sub-Catchment	1	2	3	4	5	6	7
Total Area (ha)	1.4888	4.4691	3.4569	4.836	12.4462	7.3029	0.6971
CN _N	93.38	92.32	92.00	93.49	93.08	92.20	95.16
Interlocking Tiles and Concrete Area (ha)	1.0589	2.8834	2.1376	3.1646	7.2100	4.0397	0.5732
Percent of Impervious Layer (%)	71.12	64.52	63.54	65.44	57.93	64.90	82.22
Length from outlet to farthest point (m)	225.44	845.14	446.22	282.39	1340.32	847.90	139.31
Width of overflow(m)	66.04	52.88	77.47	171.25	92.86	86.13	50.04
Highest Elevation (m)	142.5	143.9	139.6	132	140.1	142	135.9
Lowest Elevation (m)	137.4	133.3	131.1	118.2	92	115.2	132.4
Distance between highest and lowest points (m)	248.7	775.1	518.3	219.2	1286.4	770.5	150
Percent slope (%)	2.05	1.37	1.64	6.30	3.74	3.48	2.33
Drying time (days)	8	8	8	8	8	8	8

In this research, there is a collective application of multiple LIDs on each basin, three types of LIDs are chosen for this particular research area, which are Bio-retention basins (BRB), Permeable pavement systems (PPS) and Rainwater harvesting systems (RWHS). In the application of different LIDs, the following assumptions were made

- Bio-retentions basin is applied only on the pervious areas of the basins.
- PPS are applied on the parking lots and walking paths
- RWHS are applied where there was no possibility of application of above LIDs.

As the bio-retention basin is implemented in the pervious regions, there will be no alteration in the existing percentages of impervious surfaces. Conversely, when the Permeable Pavement Systems (PPS) are introduced, changes will be observed as they are applied to the impervious areas. The area allocated for the installation of LID units was strategically decided based on the availability of space within the research site. This was determined using Google Earth Pro software. The percentage of impervious areas treated by the LIDs was determined by considering factors such as the slope of the area and the potential direction of runoff. Figure 4.8 illustrates the application of LIDs on Basin 1 in the area of METU-NCC, wherein the arrows signify the direction of flow of runoff. The blue portion in the figure below represents the LIDs, while the black represents the impervious areas similarly. The number of units of each LID and the corresponding areas are specified in Table 4.6, along with the percentage reduction in the impervious areas. The percentage of area treated by the LIDs are different for different basins, the water running off the main roads is ignored in this analysis, the percent area treated by LIDs are mentioned in Table 4.7. The LID application in the other basin is implemented (See Figure A.1 to Figure A.5) here the B refers to Bio-retention system, P refers to Permeable pavement system and R for Rainwater harvesting System.



Figure 4.8. Placement of LIDs in Basin 1 (METU-NCC)

Table 4.6. Characteristics of LIDs applied in the 7 distinguish basins (METU-NCC)

Basins	BRB units	Total area of BRB units (m ²)	RWHS units	Total area of RWHS units (m ²)	PPS units	Total area of PPS units (m ²)	Percent Reduction in Impervious area after LID application (%)
1	4	1880	3	40	2	720	5
2	7	3885	5	120	2	841	3
3	3	3666	0	0	3	2970	9
4	2	7525	1	35	1	6423	13
5	5	7460	0	0	6	12700	11
6	6	7812	0	0	2	7200	10
7	0	0	1	100	0	0	0

Table 4.7. Total area treated using LIDs for each basin

Basins	Total percentage of impervious area treated (%)
1	100
2	53
3	51
4	57
5	29
6	49
7	100

For the study area of Güzeyurt town, the catchment with the highest amount of imperviousness surfaces is considered for analysis, in this case Catchment B is considered for analysis. This Catchment is again divided into Sub-catchments as shown in the Figure 4.9, the characteristic information of the catchment B is provided in the Table 4.8. The area of Catchment B can be considered as a high density residential area, To illustrate, the buildings within Subcatchment B can be categorized into four distinct types. The first type includes administrative offices like banks, municipality buildings, and communication centers. The second type comprises residential properties, which can consist of single houses, two-story houses, or apartments. However, apartments are relatively scarce and not commonly found in this particular region. The third type encompasses solely commercial establishments, such as individual shops, restaurants, or pharmacies, which are typically separate from the residential areas. The fourth type represents a combination of residential and commercial components, which is prevalent in certain parts of the town. These buildings are characterized by having shops located on the ground floor, underneath the residential units.

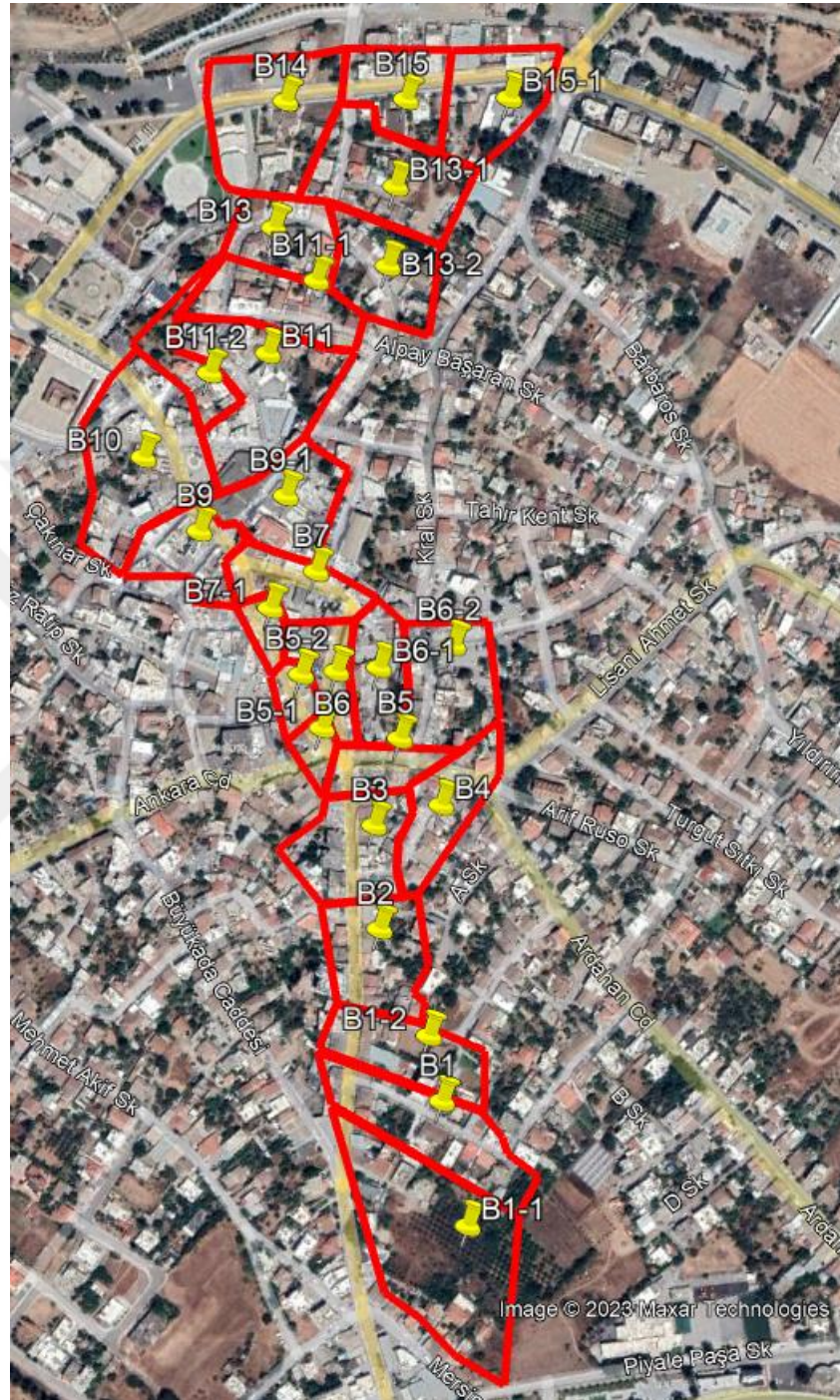


Figure 4.9. Subcatchments for Güzelyurt Catchment B

Table 4.8. Characteristic Information of Catchment B of Güzelyurt Town [99]

Subareas	Outlet	Area (ha)	%Imperv	Width (m)	%Slope
B6	J12	0.3	90	95.6	1.04
B1-1	J1	1.5	15	138.48	1.1
B1	J2	0.93	80	60	0.98
B1-2	J3	0.59	40	48.2	1.11
B2	J4	0.65	60	141.2	2.5
B3	J5	0.66	80	150.9	1.79
B4	J8	0.56	80	78.52	1
B5	J7	0.3	90	144.2	2
B5-1	J9	0.13	90	49.5	1.32
B5-2	J10	0.21	90	102.2	1.11
B6-1	J13	0.44	80	64.6	1
B6-2	J14	0.67	70	66.65	1.24
B7-1	J15	0.1	100	107.2	0.66
B7	J16	0.43	95	45.9	1.2
B9	J17	0.41	90	44.77	1
B9-1	J18	0.5	85	119.3	0.36
B10	J22	1.1	80	121.77	1.75
B11-2	J21	0.19	90	68.2	0.3
B11	J24	0.7	80	57.61	0.8
B11-1	J25	0.62	80	79.1	1.58
B13	J26	0.45	70	137.6	1.52
B13-2	J27	0.65	60	70.36	3.2
B13-1	J28	0.9	30	127.6	1.75
B14	J32	0.91	30	161.5	0.05
B15	J29	0.44	60	144	0.16
B15-1	J30	0.61	60	138.7	0.71

These subareas does have various Junctions and Conduits in the Network, the information to Junctions and Conduits is provided in the Table 4.9 & Table 4.10. The Table 4.10 provides comprehensive details regarding the conduits, including the inlet node, outlet node, conduit length, pipe roughness, pipe shape, and diameter for each conduit. For instance, Conduit 32 is characterized as a

rectangular channel made of concrete. It has a bottom depth of 0.6 m and with a maximum depth of 0.4 m.

Table 4.9. Characteristic Information of Junctions of Catchment B of Güzelyurt Town [99]

Junctions	Invert Elev	Max. Depth m	Junctions	Invert Elev	Max. Depth m
J1	48.532	0.8	J17	43.29	1.1
J2	48.085	0.8	J18	42.8	1.1
J3	47.719	0.8	J21	42.213	0.8
J4	46.151	0.8	J22	42.323	0.8
J5	45.669	0.8	J23	41.91	1.1
J6	45.594	0.8	J24	41.37	1.3
J7	45.632	0.8	J25	40.63	1.15
J8	45.873	0.8	J26	39.13	1.2
J9	44.948	0.8	J27	38.75	1
J10	44.326	0.8	J28	36.98	1.3
J11	44.06	1	J29	37.487	0.8
J12	44.504	0.6	J30	37.656	0.8
J13	45.002	0.6	J31	36.84	1.4
J14	45.421	0.6	J32	37.478	0.8
J15	43.66	1.2	J33	42.74	1.1
J16	43.41	1.2			

Table 4.10. Data for Conduits in Catchment B for Güzelyurt Town [99].

Conduits	From Node	To Node	Length (m)	Pipe size (mm)	Shape	Roughness
C1	J1	J2	53.25	500	Circular	0.012
C2	J2	J3	41.44	500	Circular	0.012
C3	J3	J4	79.86	500	Circular	0.012
C4	J4	J5	79.74	500	Circular	0.012
C5	J5	J6	21.52	500	Circular	0.012
C6	J9	J10	57.52	500	Circular	0.012
C7	J6	J9	45.84	500	Circular	0.012
C8	J8	J7	67.38	500	Circular	0.012
C9	J7	J6	5.49	500	Circular	0.012
C10	J10	J11	49	500	Circular	0.012
C11	J14	J13	42.29	300	Circular	0.012
C12	J13	J12	53.72	300	Circular	0.012
C13	J12	J11	3.8	300	Circular	0.012
C14	J11	J15	48.85	500	Circular	0.012
C15	J15	J16	39.7	500	Circular	0.012
C16	J16	J17	15.99	500	Circular	0.012
C17	J17	J18	76.41	500	Circular	0.012
C19	J22	J21	64.38	500	Circular	0.012
C20	J21	J23	4.74	500	Circular	0.012
C21	J23	J24	30.48	500	Circular	0.012
C22	J24	J25	58.64	500	Circular	0.012
C23	J25	J26	87.3	500	Circular	0.012
C24	J26	J27	19.72	500	Circular	0.012
C25	J27	J28	85.04	500	Circular	0.012
C26	J28	J31	3.76	500	Circular	0.012
C27	J30	J29	65.43	500	Circular	0.012
C28	J29	J31	10.88	500	Circular	0.012
C29	J32	J31	7.06	500	Circular	0.012
C30	J31	OUT1	60	500	Circular	0.012
C31	J18	J33	4	500	Circular	0.012
C32	J33	J23	107.93	400×600	Rectangular	0.013

The implementation of Low Impact Developments (LID) in Güzelyurt Town follows a similar approach to the LID application in the METU-NCC research area.

The pervious areas within the catchment are transformed into Bio-retention areas which are represented by blue color, while the pavements and parking lots are converted into permeable pavements which are represented by Yellow color. Additionally, houses and buildings with substantial roof areas are equipped with Rainwater Harvesting tanks. To illustrate the strategic placement of these LIDs, consider the example shown in the Figure 4.10.

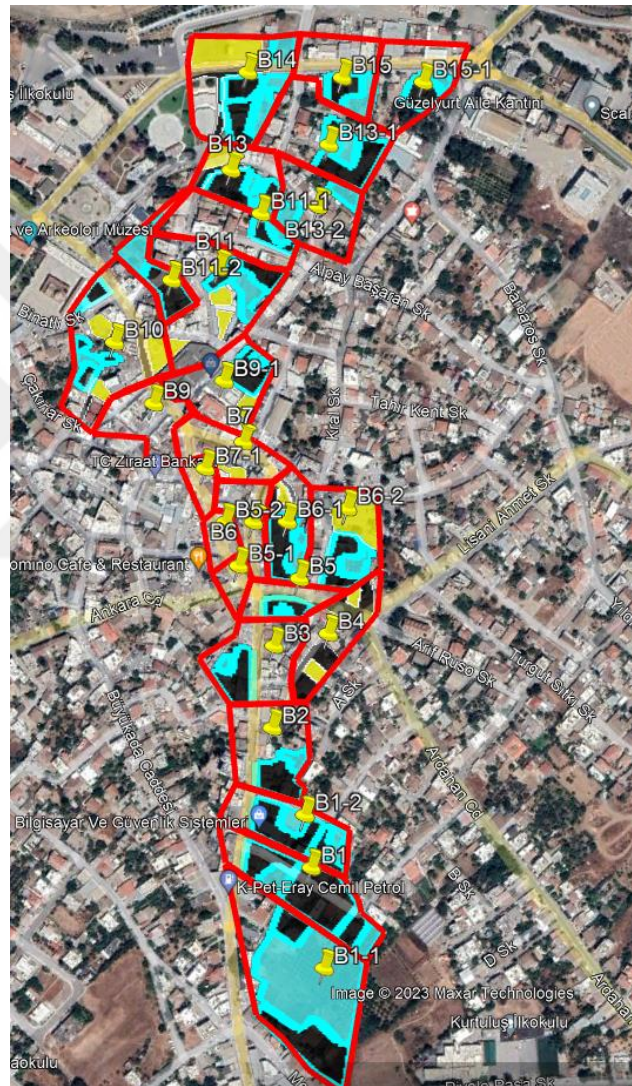


Figure 4.10. LID application in Catchment B of the Güzelyurt town

The blue areas represent the locations where Bioretention systems are employed, effectively treating stormwater runoff. The yellow areas indicate the installation of

permeable pavements. Specifically, the placement of permeable pavements is chosen strategically, taking into account the presence of parking lots adjacent to buildings. This location allows for the treatment of both the water falling directly on the pavement and the water from the surrounding areas, optimizing the efficiency of the system, which can be seen from the Figure 4.11.

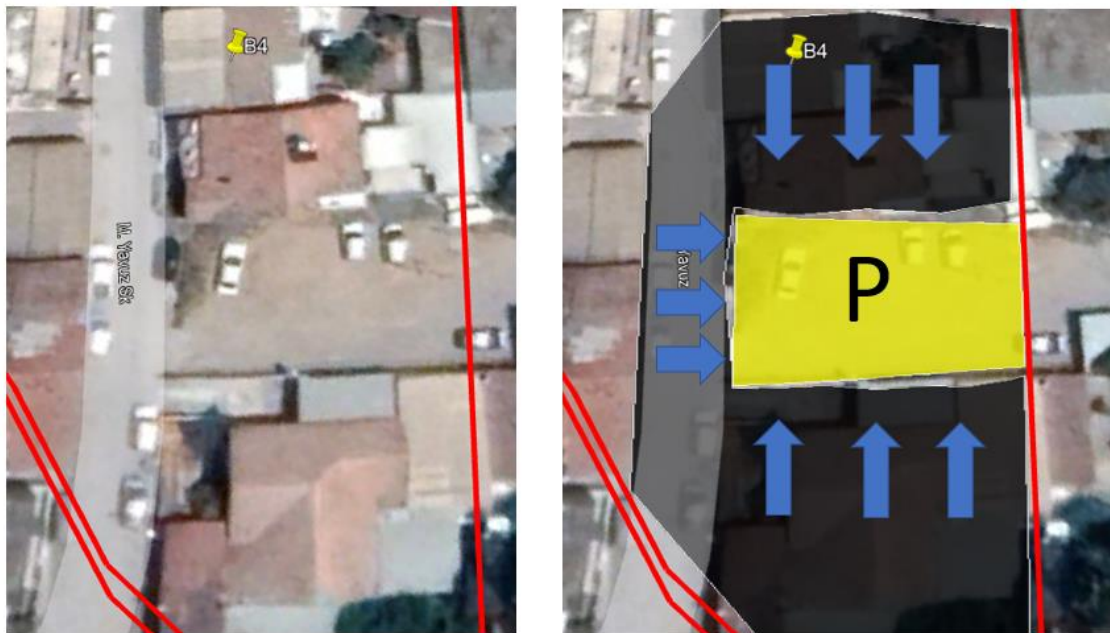


Figure 4.11. LID application of Permeable Pavement in Subarea B4

The image on the left in the Figure 4.11 is a residential area with houses surrounding the parking lot, this type of areas are perfect for application of permeable pavement, the image on the right is the implementation of permeable pavement, the P refers to permeable pavement and the blue arrows is shows the flow of water towards the system. The total number of Bioretention, permeable pavement units and Rainwater harvesting systems along with their areas and tank sizes have been tabled below in the Table 4.11.

Table 4.11. Number of Units of LIDs in Catchment B of Güzeyurt town

Sub-catchments	Bioretention Area/ Unit (m2)	Permeable Pavement Area/ Unit (m2)	Rainwater Harevsting Tank capacity (m3)	Number of Units
B1-1	6000	-	-	1
B1	1142	-	3	1
B1-2	1029	-	-	1
B2	407	-	42	1
B3	173	-	54	1
B5	100	-	22	1
B4	-	500	23	1
B5-1	-	-	17	1
B5-2	-	-	16	1
B6	-	-	26	1
B6-1	580	230	6	1
B6-2	588	1650	12	1
B7-1	-	-	15	1
B7	-	360	41	1
B9	-	-	38	1
B9-1	124	400	26	1
B11-2	400	-	-	1
B10	434	1450	53	1
B11	-	650	49	1
B11-1	150	-	46	1
B13	180	650	15	1
B13-2	800	-	29	1
B13-1	400	-	27	1
B15	200	-	34	1
B15-1	0	-	28	1
B14	700	2000	-	1

When establishing LID regulations in a particular subcatchment, it is also essential to alter the amount of impervious area. For instance, the implementation of a LID control that occupies an area equivalent to A_{LID} must be considered if a subcatchment has an area of A (in square meters) with $f\%$ impervious area. The area occupied by LID controls (A_{LID}) is calculated by dividing the total number of LID controls (n_{lid}) deployed inside the subcatchment by the area of each control (a_{lid}). The percentage of the treated area ($lid_{treated}\%$) is also taken into account. Therefore, Equations (9) and (10) can be used to determine the area contributing to runoff and the runoff coefficient, respectively. The inflow can be calculated using the equations below.

$$A_{initial} - A_{LID} = A_{final} \quad (9)$$

$$C_{final} = (f \times lid_{treated}) + A_{LID}/A_{final} \quad (10)$$

$$\text{Total inflow} = (A_{final} \times C_{final} \times i)/(a_{lid} \times n_{lid}) \quad (11)$$

where;

$A_{initial}$ is the total subcatchments area before applying LID control

A_{LID} is the area that the LID control occupies

C_{final} is the final runoff coefficient after applying LID control

A_{final} is the final area

i is rainfall intensity

f is percent of impervious area

n_{lid} is number of LID units

a_{lid} is area of each LID unit

The application of LID within the Software is convenient, there is a section of LID controls where different LID options are listed, a specific LID which is applied can be selected from the list and applied in for any specific catchment, the inputs need to be entered, inputs such as the technical parameters must be defined and their values must be entered, in case of Bio-retention application, which is given in the Figure 4.12. different parameters must be entered to define a LID, such as Berm Height, vegetation ratio, Surface roughness etc. After defining a LID, it can be applied in any Sub-catchment by selecting the already defined LID and entering some technical parameters such as Area of LID, Number of Units and % of Area treated etc. As shown in the Figure 4.13

LID Control Editor

Control Name:

LID Type:

Diagram: A cross-section of a bioretention unit showing layers: Surface (with vegetation), Soil, and Storage. Arrows indicate flow from Surface to Soil to Storage, and an optional Drain* at the bottom. A large blue arrow points down from the Storage layer.

*Optional

Buttons: OK, Cancel, Help

Surface	Soil	Storage	Drain
Berm Height (in. or mm)			
Vegetation Volume Fraction			
Surface Roughness (Mannings n)			
Surface Slope (percent)			

Values entered in the Surface tab:

- Berm Height (in. or mm): 100
- Vegetation Volume Fraction: 0.0
- Surface Roughness (Mannings n): 0.1
- Surface Slope (percent): 1.0

Figure 4.12. Defining Bioretention Unit under LID Control Editor in SWMM

LID Usage Editor

LID Control Name: **Bioretention**

☐ LID Occupies Full Subcatchment

Area of Each Unit (sq ft or sq m): **34**

Number of Units: **1**

% of Subcatchment Occupied: **1.133**

Surface Width per Unit (ft or m): **34**

% Initially Saturated: **0**

% of Impervious Area Treated: **48**

% of Pervious Area Treated: **0**

Send Drain Flow To:
(Leave blank to use subcatchment outlet)

☐ Return all Outflow to Pervious Area

Detailed Report File (Optional):

OK **Cancel** **Help**

Figure 4.13. Editing technical parameters of LID under LID Usage Editor in SWMM

4.6 Optimization of LID units

In this research, the optimization of Low Impact Development (LID) strategies was carried out through a manual approach. Initially, a unit of LID with fixed depths of soil, surface, and storage components was selected and implemented within a specific catchment. By simulating a rainfall event, the runoff was measured before and after the application of the LID. The process involved gradually increasing the size of the LID, taking into consideration the available area and the characteristics of the rainfall. For certain scenarios where the impervious area associated with an LID was lower than expected but the LID area was larger, adjustments were made manually. The goal was to ensure that the LID sizes did not exceed the necessary dimensions, thus avoiding the unnecessary waste of materials and area during implementation.

In this optimization process, two key factors were considered: the amount of impervious area treated by each LID and the reduction of runoff achieved. The size of each LID was manually adjusted to an optimized level where it effectively treated the impervious surface area and reduced runoff without the inclusion of any extra, redundant area. The aim was to maximize the efficiency of each LID while minimizing waste. By iteratively adjusting the LID sizes based on these controlling factors, an optimal configuration was achieved. This approach ensured that the implementation of LIDs was precisely tailored to the specific requirements of the catchment, considering both the impervious surface area to be treated and the desired reduction in runoff. The manual optimization process allowed for a fine-tuned implementation, minimizing unnecessary resource utilization and maximizing the effectiveness of the LID strategies. Through this research, it has been demonstrated the importance of optimizing LID strategies to achieve the most efficient and effective results. By carefully adjusting the sizes of LIDs based on controlling factors such as treated impervious area and runoff reduction, we can ensure the successful implementation of LID practices while minimizing any potential waste. This manual optimization approach contributes to the overall sustainability and cost-effectiveness of LID projects, ultimately leading to better stormwater management and environmental outcomes.

4.7 Rainwater Harvesting (RWH)

The application of rainwater harvesting tanks requires careful consideration to ensure the appropriate size of the tanks. It is crucial to find a balance where the tank size is neither too small nor too large. In this case study, the calculation of tank size is based on the available roof area. To determine the tank size, the buildings in the Güzelyurt catchment are categorized into different groups based on their rooftop area. Group 1 comprises buildings with a rooftop area less than 100 m², Group 2 includes buildings with a rooftop area ranging from 100 to 200 m²,

Group 3 consists of buildings with a rooftop area between 200 to 300 m², and Group 4 includes buildings with a rooftop area of 300 to 400 m². By categorizing the buildings into these groups, we can better assess the appropriate tank size needed for rainwater harvesting. This approach ensures that the tank sizes are tailored to the specific roof areas, optimizing the collection and storage of rainwater. It is essential to consider the unique characteristics and requirements of each building group to determine the most suitable tank size for effective rainwater harvesting. The tank sizes are calculated using the equation 12 below,

$$\text{Tank Size} = A \times C \times I \quad (12)$$

where;

A = Footprint of the area in m²

C = Runoff coefficient

I = Intensity of Rainfall in m/year.

Here the rainfall considered is the average rainfall per year in the Güzelyurt Town which in the period of 1978 to 2015, which is 270 mm/year [97]. When determining the tank size for buildings with rooftop areas ranging from 100 m² to 200 m², the midpoint value of this range is used in the calculation equation. This approach ensures that the tank size is representative of the average size within this specific range of buildings. By considering the medium value, the calculated tank size aligns more closely with the typical requirements of buildings in this size category, furthermore, It is assumed that only 10% of the total water from the precipitation will be stored. This methodology aims to provide a practical and balanced approach in determining the appropriate tank size for rainwater harvesting in buildings within the specified range. The buildings with different rooftop areas are classified and tabled in the below Table 4.12. In the research area of Güzelyurt Town, the formula mentioned earlier in the equation 11 was used to determine the tank sizes. This formula considers the rooftop area of buildings within specific

groups and calculates the tank size based on the average size within each group, the Table 4.13 shows the tank sizes used in the study area of Guzelyurt town. This approach ensures that the tank sizes align closely with the typical requirements of buildings in that specific range. In contrast, for the second research area which is METU-NCC, a different method was adopted. Due to the availability of ample free space in this area, as there are many large buildings in the basins, such as Administrative, Dormitories and Academic buildings etc. The larger rainwater harvesting tanks were used. The aim was to explore the potential impact of larger tank sizes on reducing runoff in an area with more available

Table 4.12. Categorization of Buildings for Güzelyurt Town

Catchments	<100 m ²	100- 200m ²	200- 300m ²	300- 400m ²
B1	0	1	0	0
B2	1	8	2	1
B3	4	12	0	2
B4	5	6	0	0
B5	1	2	3	0
B5-1	3	3	1	0
B5-2	5	2	1	0
B6	1	5	2	0
B6-1	0	2	0	0
B6-2	1	2	1	0
B7-1	4	2	1	0
B7	8	11	0	0
B9	9	4	2	1
B9-1	0	4	0	2
B10	1	5	6	1
B11	1	8	2	2
B11-1	5	4	3	2
B13	0	0	3	0
B13-1	1	7	1	0
B13-2	0	8	1	0
B15	0	1	2	3
B15-1	4	0	2	2

space for installation. This approach allowed for an investigation into the effectiveness of larger tanks in mitigating runoff. By incorporating these different

methodologies, the aim was to compare the outcomes of using a standardized calculation approach in one area with the outcomes of employing random allocation based on runoff reduction in the other. This approach allowed for a comprehensive analysis of the effectiveness and suitability of different rainwater harvesting tank sizing methods in varying contexts.

Table 4.13. Rainwater Harvesting calculated Tank sizes

Groups	Areas (m²)	Tank sizes (m³)
1	< 100	1
2	100 - 200	3
3	200 - 300	5
4	300 - 400	8.5

4.8 Rainfall Scenario

In this research, two distinct research areas, METU NCC and Guzelyurt Town, were investigated to address specific challenges related to rainfall runoff and flooding. The METU NCC research area focused on a rainfall event with an intensity of 22 mm/hr, representing the monthly average rainfall in the area. The objective was to analyze the runoff patterns and propose effective strategies for managing runoff in controlled conditions. In contrast, the Guzelyurt Town research area presented a different scenario with dense residential development and a history of flooding. To tackle this issue, various rainfall events that occurred in the region were considered, including a significant rainfall event with an intensity of 26 mm/hr, which led to flooding in multiple locations. The objective was to evaluate the efficiency of Low Impact Development (LID) measures in reducing flood risks and effectively managing stormwater in densely populated residential zones. In the case of Guzelyurt Town, two types of design rainfall patterns were considered to

simulate different rainfall scenarios. The first type was the constant rainfall pattern, where the rainfall intensity remained constant throughout the one-hour duration. This approach allowed for the analysis of the response of stormwater systems under a consistent rainfall intensity. The second type of design rainfall considered was the varying rainfall pattern, which aimed to replicate real-world rainfall events with varying intensities over time. This pattern consisted of a 60-minute duration, divided into four time intervals of 15 minutes each. The rainfall distribution for each interval was as follows: 20% of the total rainfall occurred in the first 15 minutes, 40% in the subsequent 30 minutes, 30% in the following 45 minutes, and the remaining 10% in the final 15 minutes. By capturing the temporal variation in rainfall intensity, this design aimed to better simulate actual rainfall events.

Both design rainfall patterns were used in conjunction with a time step of 15 minutes to model the hydrological response and assess the performance of the implemented LID measures as shown in the Figure 4.14, the Figure (a) shows the constant rainfall whereas the Figure (b) shows the varying rainfall. This approach enabled a comprehensive analysis of stormwater management strategies under different rainfall scenarios and provided insights into the effectiveness of LID techniques in mitigating flood risks in Guzelyurt Town.

By incorporating different rainfall events and LID designs in the analysis of Guzelyurt Town, a comprehensive understanding of the challenges faced in densely populated areas and the effectiveness of LID strategies in reducing flooding risks was obtained. Comparing the outcomes of both research areas will provide valuable insights and recommendations for stormwater management in diverse contexts, contributing to the advancement of knowledge in the field.

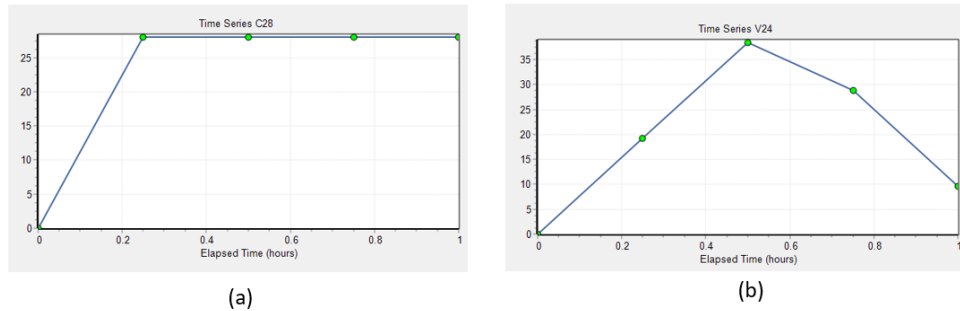


Figure 4.14. Types of Design rainfall

4.9 Life Cycle Assessment (LCA)

LCA is a technique used to assess the environmental effects of a process, product, or activity over the course of its complete life cycle, which includes the collection of raw materials, manufacture, transportation, usage, and disposal or recycling. It also assesses environmental effects such as resource depletion, ozone depletion, acidification, global warming, and acidification. LCA is essential for making informed decisions and identifying areas for improvement in terms of sustainability. It is also widely accepted and used by organizations and nations, and is governed by ISO 14040/44 which provides guidelines and standards for conducting LCA studies and making comparisons across different products or industries. This study's goal is to comprehensively assess and contrast the advantages and effects of using LID methodologies at the Middle East Technical University's Northern Cyprus Campus. The project's scope includes every stage of the life cycle of a LID, including the procurement and production of raw materials, transportation to the construction site, and the decommissioning site at the end of its useful life. However, for this particular study, no specific data on the decommissioning and end-of-life scenario of LIDs was available. The study also considers the decreases in pollutant loads in treated storm-water effluent as it exits the individual LIDs.

An detailed evaluation was done to determine the environmental effects of the various Low Impact Development (LID) strategies used in Guzelyurt Town. The environmental performance of the LID measures—Bioretention basins, Permeable Pavement systems, and Rainwater Harvesting tanks—was compared to that of conventional stormwater management methods. The traditional technique involved resizing existing drainage pipes to handle increased runoff. The assessment aimed to understand the overall environmental effects of the LID practices, including resource usage, energy consumption, greenhouse gas emissions, and other relevant impacts. By quantifying and comparing these impacts with the traditional stormwater management technique, insights were gained into the sustainability and effectiveness of the implemented measures. The assessment involved analyzing the different stages of each LID practice's life cycle, such as material extraction, production, construction, operation, maintenance, and end-of-life disposal or recycling is not considered due to lack of sufficient data.

The results of the assessment provided a comprehensive understanding of the potential environmental benefits associated with the LID practices in both the research areas. The findings informed decision-making processes regarding stormwater management strategies and highlighted the broader implications of implementing sustainable drainage solutions in urban areas.

4.9.1 OpenLCA Software

In this study, for conduction life cycle assessment, openLCA software is used, it is a free and open-source software tool used for LCA studies. A product or service's environmental effects are measured using the LCA technique at every stage of its life cycle, from the extraction of raw materials to the product's eventual disposal. Because it offers a convenient and user-friendly framework for modeling the life cycle inventory of a good or service, it is used to undertake LCA investigations. It enables users to quickly enter data on a product's or service's material and energy inputs, outputs, and associated environmental impacts at each stage of its life cycle.

This data can then be used to generate comprehensive life cycle inventory reports and impact assessments. It also has a large library of pre-existing data for various products, activities, and processes which can be used to conduct LCA studies. It also allows for the creation of custom data sets, thus making it more flexible [108].

The following Figure 4.15, shows the database elements of OpenLCA software which needed to be defined under the software for carrying out a Life cycle assessment. OpenLCA's databases encompass a range of essential components, including project details, product information, system configurations, process descriptions, LCIA methods, flows and their properties, unit groups, currencies, locations, actors, sources, indicators, and parameters. Within these databases, actors refer to individuals involved in data provision and model modification, currencies enable cost assignment and life cycle costing, locations are significant for regionalized assessments, sources refer to referenced literature, unit groups categorize measurement units, flow properties describe characteristics, flows represent assessed products and materials, processes encompass production or modification activities, impact methods are imported for assessment purposes, product systems involve interconnected processes for calculating inventory and impact, projects facilitate comparison of product system variations, and indicators and parameters include social indicators, global parameters, and data quality systems.

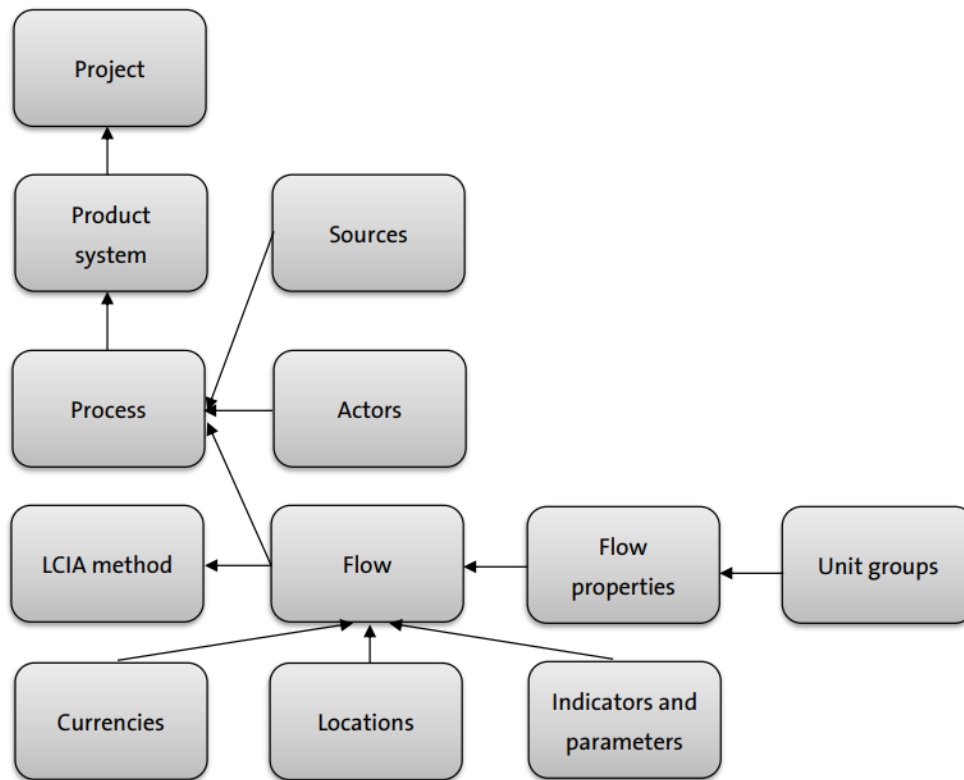


Figure 4.15. Database elements in OpenLCA software

4.9.2 System Boundary

The scope of this study encompasses various stages of the LID units, including raw material acquisition, transportation, construction, and maintenance. In Figure 4.16, the system boundary for the construction and operation phases is illustrated, which includes the sourcing and processing of raw materials for the LID components, as well as the transportation of these materials to the construction site. By adopting this inclusive approach, a thorough assessment of the LID units' overall benefits and impacts is achieved, taking into account relevant aspects at each stage.

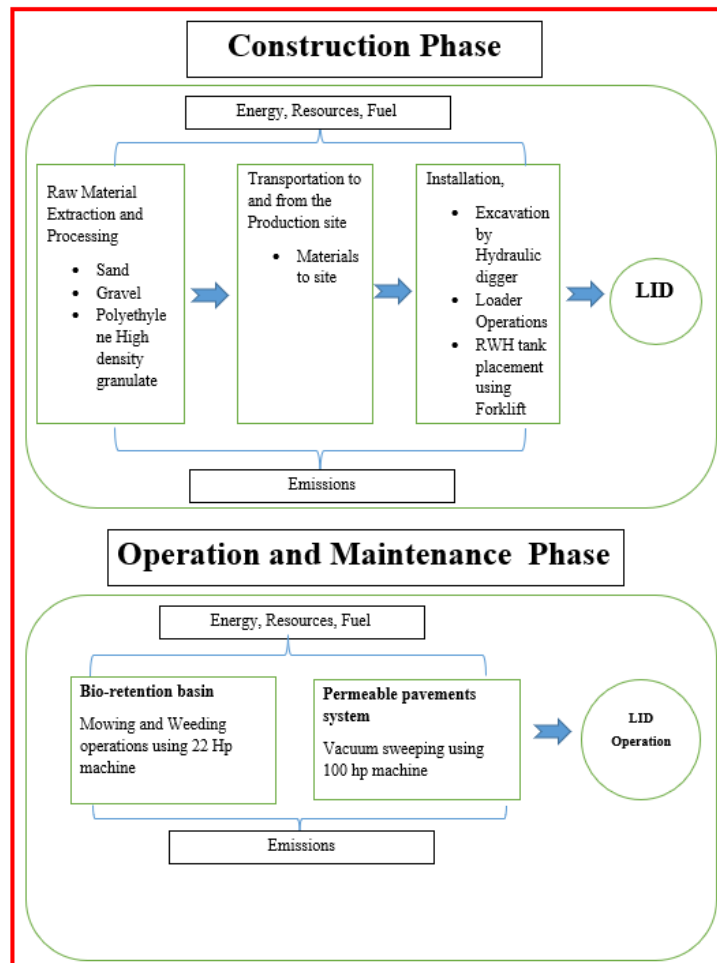


Figure 4.16. System Boundary

During the production of LIDs, many steps are incorporated one of which is Production/mining of sand, Gravel and soil as all the operations which takes place in the mining is considered with accordance to European standards, the production of sand and gravel can be seen in the Figure 4.17.

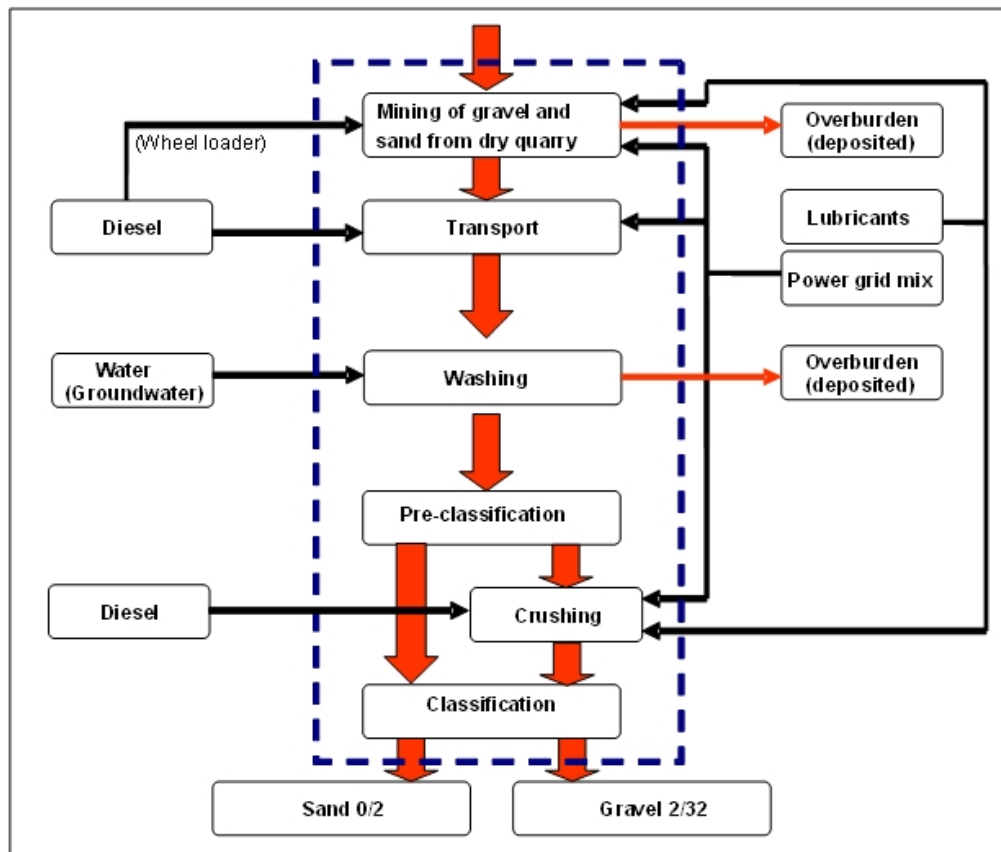


Figure 4.17. Production of Sand and Gravel [108].

The life cycle analysis of sand and gravel includes washing, sorting, and sizing of the extracted stone grains as part of the preparation of the stone for quarrying. The evaluation takes into account energy production, the availability of raw materials, and the finished product at the factory gate. However, it excludes the manufacturing facility's infrastructure and output, and transportation from the factory to the building site, which should be considered separately. The background system includes electricity and thermal energy modeled according to the country-

specific situation, as well as transport, energy carriers, and refinery products, taking into account import and domestic supply, mining and exploration techniques, and country-specific properties. Similarly other operations such as transportation and excavation are also selected from the life cycle inventory of openLCA. For the transportation part, the materials from the manufacturing unit are brought to the site and while excavation activities are taken place a nearby site is selected for disposal of debris, the selected dataset for transportation is “transport, freight, lorry 16-32 metric ton, EURO3”. This dataset reflects the service of 1 tkm freight transport in a truck with a gross vehicle weight (GVW) of 16 to 32 metric tons and an emissions class of "euro_class." It contains information on every aspect of the transportation life cycle, such as fuel use, emissions, and road conditions. The Tremove and EcoTransIT data are used to calculate the average load factors. The GVW, as well as the amount of exhaust and non-exhaust emissions, are determined by the lorry size and load factor. The HBEF model is used to calculate fuel consumption and exhaust emissions, while non-exhaust emissions are taken into consideration as weight-dependent byproducts. Based on gross tons kilometer and vehicle kilometer performance, road infrastructure costs and environmental interventions are distributed. According to the ecoinvent 2007 study on transportation services [111], information on the creation, upkeep, and disposal of the vehicle. The production of RWH tanks is proceeded in two operations first is the production of polyethylene high density granulates and using the operation of injection molding, the tanks are produced. The dataset chosen for production of polyethylene high density granulates is “Polyethylene High Density Granulate (PE-HD), production mix, at plant”. Similarly for dataset chosen for Injection molding operation to produce/ Manufacture the RWH tanks is “market for injection molding”.

During the operation phase of the research, two different types of machines are utilized for specific purposes. The first machine is a 22 horse power machine that is utilized for weeding operations at bio-retention basins. The second machine is a 100 horse power machine that is used for vacuum sweeping of permeable

pavement systems. These operation activities are conducted twice a year, and each operation lasts for one hour. It is important to note that the lifetime of LID systems is uncertain, therefore, an average lifetime of 50 years is used in this research. This assumption allows for a consistent and measurable benchmark for the research's analysis and conclusions. The use of these machines, and their specific horse power, is crucial in maintaining and preserving the longevity and effectiveness of LID systems. The operation phase is an essential aspect of the overall maintenance and upkeep of LID systems, and it is important that the correct equipment and techniques are utilized to ensure their continued functionality. The processes involved through the production of Bio-retention unit is mentioned in the below Figure 4.18.

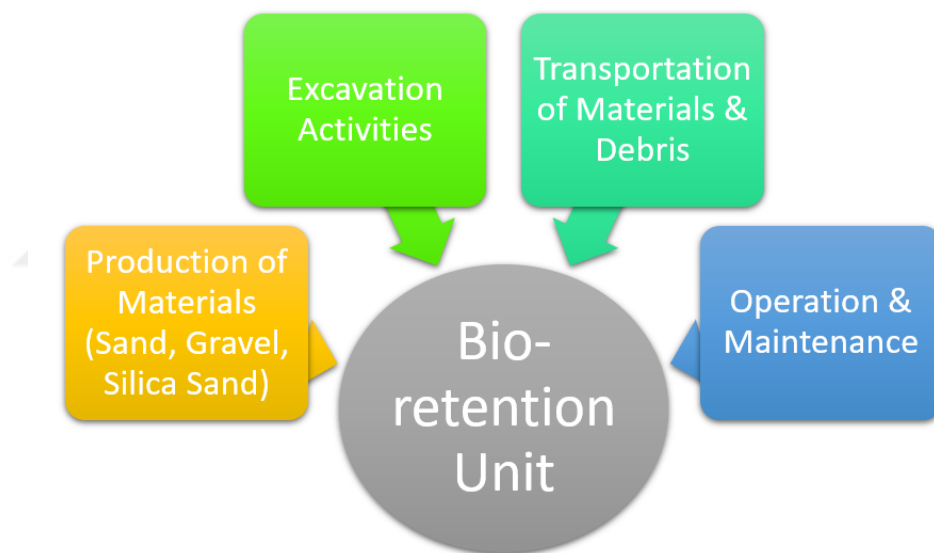


Figure 4.18. The processes involved in Production of Bio-retention Unit

Similar to the Figure 4.18, the other LIDs are also produced keeping in mind the necessary operations and processes involved during their production.

4.9.3 Traditional Stormwater Management Solution

In this study, comparison of Low Impact Development (LID) strategies with traditional stormwater management solutions is conducted. The traditional approach involves resizing the conduits in flood-prone areas. However, for the purpose of conducting a Life Cycle Assessment (LCA), it is needed to consider the production of concrete pipes that will be used in this case study. To obtain the necessary information regarding the materials required for concrete pipe production, we consulted with Prof. Dr. Ceren Ince from METU-NCC. Dr. Ince is an expert in materials science. Appendix B contains the obtained data on material quantities per cubic meter (m³). By incorporating this data into LCA, it can assess the environmental impacts associated with the production of concrete pipes. This information is crucial for a comprehensive evaluation of the sustainability of traditional stormwater management solutions compared to LID strategies.

The sand and gravel require will be produce as mentioned in Section 4.8.2. The cement required in the process of manufacturing concrete pipes will be produced according to the dataset given in the OpenLCA software. Cement, a hydraulic binder, is an inorganic material that, when combined with water, forms a paste. This paste undergoes hydration reactions and processes, leading to its setting and hardening. Even when submerged in water, it maintains its strength and stability. Portland cement (CEM I) primarily consists of Portland cement clinker with minor additional components. The clinker accounts for at least 95% of the total constituents. During manufacturing, calcium sulphate is incorporated to regulate the setting of Portland cement (CEM I).

The assessment of a cement plant includes activities such as raw material extraction, raw meal preparation, clinker burning, cement grinding, and dispatch. Various clinker burning technologies, including dry, semi-dry/semi-wet, and wet processes, are considered. The supply chain of raw materials, fuels, and electricity is also taken into account, encompassing their extraction, preparation, and

transportation. Regarding the background system, the electricity mix employed is based on the CEMBUREAU-specific mix derived from member countries' electricity compositions in proportion to their respective cement production. In cases where specific data is unavailable, certain data sets from the GaBi databases 2006 are utilized. All relevant and known transportation processes are included, employing ELCD data. Energy carriers and raw materials are modelled based on the European context, utilizing the ELCD database. In the absence of ELCD data, data sets from the GaBi databases 2006 are utilized, the production of the cement is shown in the Figure 4.19.

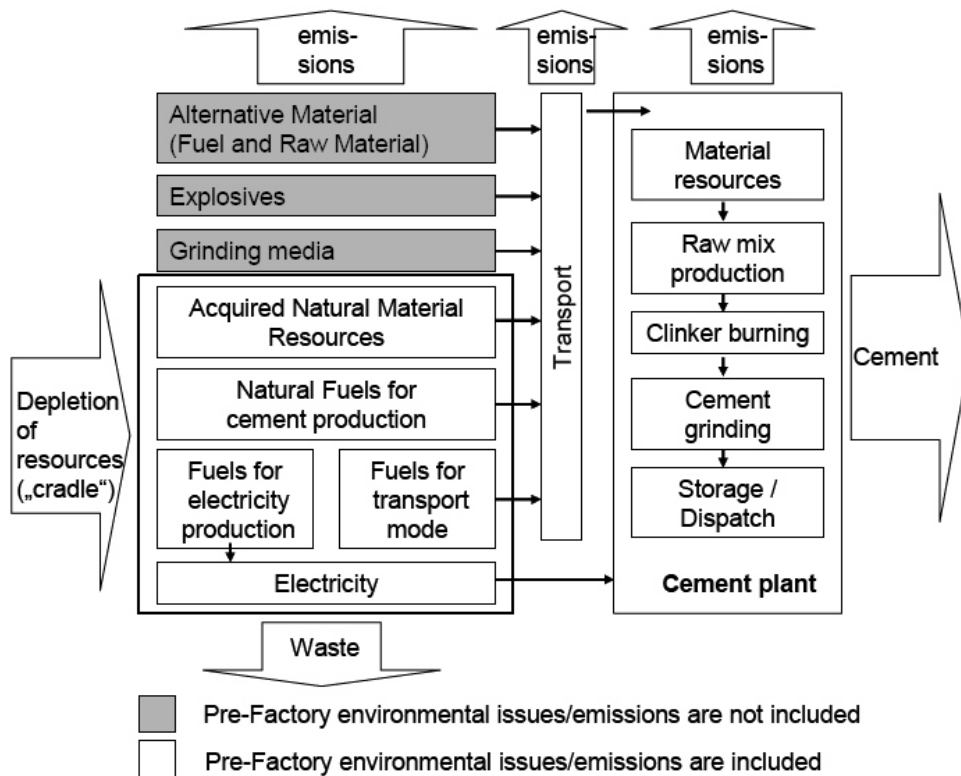


Figure 4.19. Production of Cement [108]

Similarly, production of other such materials and their emissions are considered in the analysis.

4.9.4 Impact Assessment Method

A program named TRACI 2.1 (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts) is used in the study on evaluating environmental effects. In order to encourage the creation of more sustainable goods, processes, facilities, businesses, and communities, this tool has been specifically built to address sustainability metrics, life cycle impact assessment, industrial ecology, and process design impact assessment. The use of TRACI 2.1 enables a thorough quantification of the numerous stresses that may have an impact on the environment. Ozone depletion, global warming, acidification, eutrophication, photochemical smog generation, human health impacts from particulates, human health effects from cancer, human health effects from noncancer, ecotoxicity, and consequences from the depletion of fossil fuels are some of these stressors. Future iterations of TRACI will contain the measurement of land and water consumption, according to ongoing research. The initial release of TRACI occurred in August 2002, and TRACI 2.0, an improved version, was released in 2011 [106]. The Environmental Protection Agency (EPA) in the United States is the organization that created this tool. The environmental effects of Low Impact Developments (LIDs) in comparison to conventional stormwater management strategies will be evaluated in the research using TRACI 2.1.

The fundamental approaches inside TRACI use the quantity of chemical emission or resource consumption and the predicted potency of the stressor regardless of whether the analysis is being undertaken within an LCA, process design, or sustainability metrics foundation. For each impact category, the most accurate models and data are used to evaluate potency. There is international agreement on the relative potency of the chemicals listed for some impact categories, such as probable ozone depletion and global warming effects. The relative potency for other impact categories may be based on models based on chemical and physical principles and/or experimental data. Below are descriptions of each impact

category that go into more detail on the modelling that underpins each one. The practitioner is advised to keep the location constant with each stressor in some impact categories where the location of the emission or resource employed affects the stressor's potency. In these situations, each stressor has a different potency factor at each of the locations rather than just one potency factor overall. To determine the overall impact of the study, the calculations should then be made at each location and then added up. For instance, if a destiny factor (F) and potency factor (P) are present in an impact category (i), the site-specific analysis could be calculated as follows.

$$I^i = \sum_s \sum_x \sum_m F_{xms}^i P_{xms}^i M_{xms} \quad (13)$$

where,

I^i = the potential impact of all chemicals (x) for a specific impact category of concern (i)

F_{xms}^i = the fate of chemical (x) emitted to media (m) at site (s) for impact category (i)

P_{xms}^i = the potency of chemical (x) emitted to media (m) at site (s) for impact category (i)

M_{xms} = the mass of chemical (x) emitted to media (m) at site (s)

The location particular to the site is frequently not used. One characterisation element is offered for usage globally, for instance, for some specific effect categories when geography does not significantly affect the fate, transport, or potency (such as global climate change and stratospheric ozone depletion). At other times, the precise sites of the emissions are unknown for a given study [106]. In these cases, as all effect categories provide non-site-specific characterization, extra site-generic characterization variables may be applied. In these circumstances, the universal equation with regard to location would be:

$$I^i = \sum_{xm} CF_{xm}^i \times M_{xm} \quad (14)$$

where,

I^i = the potential impact of all chemicals (x) for a specific impact category of concern (i)

M_{xms} = the mass of chemical (x) emitted to media (m) at site (s)

CF_{xm}^i = the characterization factor of chemical (x) emitted to media (m) for impact category (i)

Despite the fact that many of the impact factors were available for site-specificity in the initial release of TRACI, the majority of TRACI users have not been using the site-specific features, which are divided into various categories. This debut of The US average characterisation will be the main focus of TRACI 2.1, as explained below. Characterization factors are available for the media indicated in Table 4.14 for emission-related categories.

Table 4.14. Characterization For each effect category, factors are provided for the media [106].

Impact Category	Media
Ozone Depletion	Air
Global Climate	Air
Acidification	Air, Water
Eutrophication	Air, Water
Smog Formation	Air
Human Health Particulate	Air
Human Health Cancer	Urban Air, Nonurban Air, Freshwater, Seawater, Natural Soil,
Human Health Non-Cancer	Urban Air, Nonurban Air, Freshwater, Seawater, Natural Soil,

	Agricultural Soil
Ecotoxicity	Urban Air, Nonurban Air, Freshwater, Seawater, Natural Soil, Agricultural Soil

4.10 Installation and Specification of LIDs

LID practices, such as bio-retention basins, permeable pavement systems, and rainwater harvesting tanks, manage stormwater runoff and reduce pollutants in local waterways. Bio-retention basins filter pollutants and infiltrate clean water back into groundwater and Permeable pavements serves the similar purpose. Installation of these LIDs requires excavation, grading, drainage layers and vegetation. The SWMM software allows flexibility in designing the configuration of BRBs, PPSs, and RWH. In this case, the SWMM software gives us flexibility to design the configuration of LIDs. Figure 4.20. shows the layers whose dimensions can be altered in SWMM software

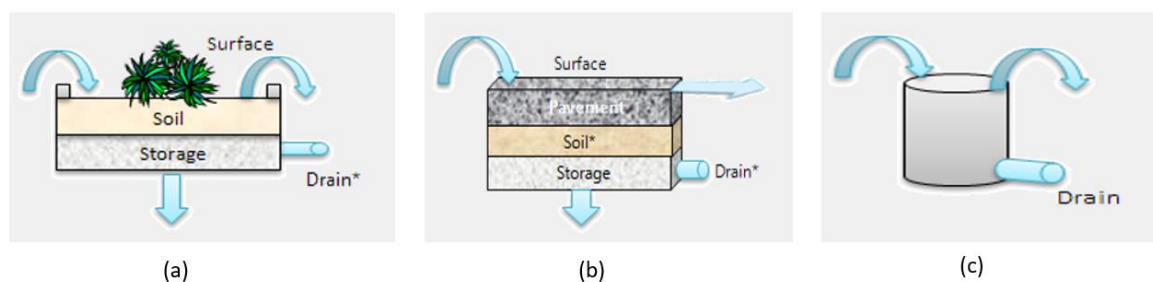


Figure 4.20. LID Designs in SWMM Software

The bioretention basin plays a vital role in implementing LID practices and its design and configuration significantly influence its effectiveness in managing stormwater runoff. The SWMM software manual offers valuable guidance on the design specifications for bioretention basins. These recommendations include a minimum depression depth of 0.3 meters (1 foot), a surface area of at least 3 square

meters (10 square feet) per hectare (2.47 acres) of drainage area, a storage volume of at least 0.01 cubic meters (0.25 cubic feet) per hectare of drainage area, and a soil or growing medium depth of 0.3 meters (1 foot) with a minimum infiltration rate of 0.2 inches per hour.

In this specific case, a developed and well-designed and optimized bioretention system capable of effectively managing stormwater runoff while also reducing pollutants is developed. It has been prioritized to use the minimal materials during construction to minimize environmental costs. The system configuration is tailored to accommodate a rainfall event with an intensity of 22 mm/hr, ensuring its optimal performance in capturing, treating, and infiltrating stormwater runoff during rainfall.

Permeable pavement systems are specifically engineered to enable the infiltration of water through the surface of the pavement and into the underlying soil. These systems utilize porous materials such as pervious concrete or permeable pavers. During installation, the site is appropriately excavated, graded, and drainage layers are incorporated before laying the permeable pavement material. The installation process of permeable pavements follows similar steps to traditional pavements but includes additional measures to ensure effective water infiltration. In this case, it has been plan to employ permeable pavements in walking paths and parking lots, configuring the pavement with a composition of 50% porous gravel and 50% bricks. The bricks that are removed during excavation will be reused, promoting sustainability.

Rainwater harvesting tanks are designed to collect and store stormwater for future use. Typically made of High density polymer plastic, these tanks are installed underground. The installation process involves excavation, site grading, tank placement, and connection to the gutter system. These tanks offer the advantage of providing stored water for purposes such as gardening, toilet flushing, or non-potable water usage. In this case, the rainwater harvesting tanks will be

conveniently positioned adjacent to the buildings without the need for extensive excavation. They will be directly connected to the existing roof drainage outlets, simplifying the installation process. Overall, the installation of bio-retention basins, permeable pavements, and rain-water harvesting tanks require a combination of excavation, grading, drainage, and material installation. Table 4.15. shows the specification of each layer of LIDs.

Table 4.15. Specifications of LIDs

LIDs	Ponding depth (m)	Soil thickness (m)	Storage thickness (m)	Flow coefficient (No drain)	Pavement thickness (m)	Barrel Height (m)
Bio-retention basin	0.1	0.1	0.2	0	-	-
Permeable pavement	0.1	0.1	0.2	0	0.1	-
Rainwater harvesting system	-	-	-	0	-	1

4.10.1 Material Estimation for LIDs

Material used to construct an LID is really important as it helps in accurate life cycle assessment of LIDs, in most of the studies manufacturing/production of materials have the highest impact on environment [116]. When conducting a life cycle assessment, it is crucial to accurately estimate the materials needed to produce a product. In the case of 100 square meters of bio-retention basins (BRBs), permeable pavement systems (PPS), and rainwater harvesting systems (RWHS), the depth of the layers used in the construction of these products must be taken into account. The depth of the layers for each product can be found in Table 4.15. To determine the quantities of materials needed for the construction of these LIDs, it is necessary to use the densities of the materials used in the process, in conjunction with the thickness of the layers provided in Table 4.15. The equation 15 & 16 can

then be used to calculate the quantity of materials needed for the construction of these products, specifically for sand, silica sand, and gravel.

$$\text{Weight of material} = A \times D \times d \quad (15)$$

where A stands for area of a unit (m^2), D for density of the material (kg/m^3), and d for the depth of the unit (m).

$$\text{Weight of the Material for RWH tanks} = \text{Total Volume of Material} \times \text{Density of the Material} \quad (16)$$

$$\text{Total Volume} = \text{Volume (Sides)} + \text{Volume (Top \& Bottom)}$$

$$\text{Volume (Sides)} = \pi \times D \times L \times T$$

$$\text{Volume (Top \& Bottom)} = \frac{\pi D^2}{4} \times T \times 2$$

where, T is the thickness in meters, D is the diameter of tank in meters, and L is the length of the tank in meters.

In order to accurately assess the emissions produced during the operation and maintenance phase, it is important to clearly state the fuel consumption in the openLCA software. In this research, two diesel-operated machines: a 22-horsepower machine for maintaining BRBs and a 100-horsepower machine for maintaining a PPS unit has been used. The fuel consumption of these machines was identified from source [109]. Operational Life of 50 years was taken into consideration, Operation and maintenance twice every year, using 22 horse power machine for weeding for Bioretention Unit of 100 m^2 will consume 4.8 liters of diesel fuel per hour [109], Considering 1 hour operation twice a year, which equals 100 hours for 50 years. Operational Life 50 years is also been considered for permeable pavements, with Operation and maintenance twice every year, using 100 horse power machine for vacuum sweeping which consumes approximately 21 liter/hour of diesel for its operation [109], Considering 1 hour operation twice a year, which equals 100 hours for 50 years. It is important to note that by clearly

stating the fuel consumption in the openLCA software, we are able to accurately determine the emissions produced by these machines during their operation and maintenance.

4.10.2 Material Estimation for Traditional Stormwater Management Solution.

In the context of material estimation, Equation 14 is commonly used to calculate the weight of materials such as sand and asphalt. However, when it comes to estimating the materials required for concrete pipe production, a slightly different formula is needed. This formula involves the calculation of volume rather than weight which is given in equation 17 and with Figure 4.21 the calculations can be clearly understood. For concrete pipe production, the volume of materials plays a crucial role in determining the quantities needed. The volume calculation takes into account the dimensions and specifications of the concrete pipe, such as length, diameter, and thickness. By accurately determining the volume, it becomes possible to estimate the amount of concrete, aggregates, and other components required for the production process.

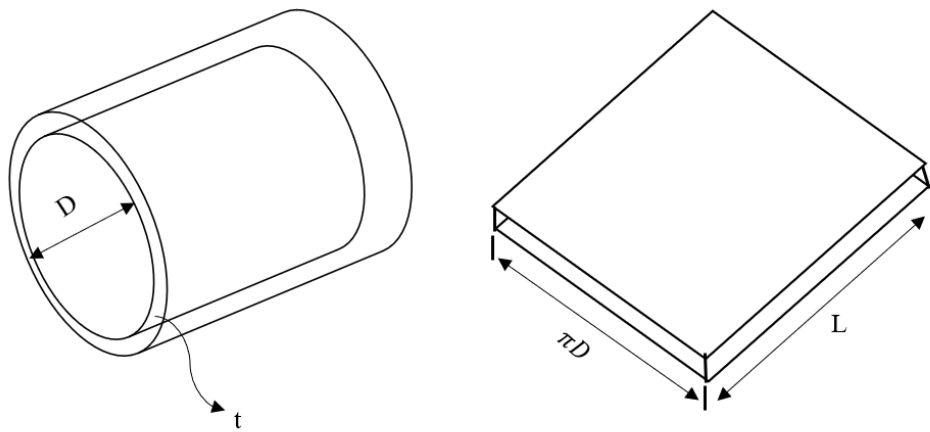


Figure 4.21. Design of a concrete pipe

$$\text{Volume of concrete pipe} = t \times L \times \pi \times D \quad (17)$$

where,

t = Thickness

L = Length of the pipe

D = Diameter of the pipe

The density of materials used throughout the calculation of materials weights, which are needed as inputs in the OpenLCA software are shown below in the Table 4.16, which have been obtained by contacting relevant stakeholders in the respective fields.

Table 4.16. Density of Construction materials

Materials	Density (Kg/m³)
Sand/ Gravel	1600
Concrete	2400
Water	1000
Soil	1700
Asphalt	2450
HDPE	950

4.11 Pollutant Buildup

Pollutant buildup is the accumulation of pollutants like nutrients, heavy metals, or bacteria in soil, surfaces, or water from sources such as residential or industrial areas. It is typically calculated using mass balance equation and wash-off functions which consider factors like precipitation intensity and land surface characteristics to determine the rate at which pollutants enter the stormwater system over time

SWMM includes built-in wash off functions for pollutants, such as EMC, EXP, and RC. In this research, EMC (Event Mean Concentration) is used, which is the average concentration of a pollutant in runoff during a storm event. EMC values for residential areas in SWMM manual vary depending on the pollutant and location. For example, EMC for TSS in residential areas can range from 50 to 110 mg/L and for TP it can be around 0.1 mg/L. However, these values can vary based on site conditions, land use, and management practices. In this case, EMC values of Residential area are used for the analysis. In this research, the EMC values are obtained from SWMM 5.2 manual [117]. The values in this manual are again derived from NSQD (National Stormwater Quality Database), in the further analysis the values which are used can be seen in Table 4.17.

Table 4.17. EMC values for Pollutants [88].

Pollutants	EMC (mg/L)
Total suspended solids (TSS)	101
Biological Oxygen demand (BOD)	10
Chemical Oxygen demand (COD)	0.073
Total Nitrogen	1.9
Total Zinc	0.135
Total Copper	0.033
Total Lead	0.144
Nitrate	0.36
Nitrite	0.736
Phosphorus	0.383

4.11.1 Sensitivity Analysis

Sensitivity analysis evaluates the impact of input parameters on results in sustainable stormwater management design studies. It is used to identify critical parameters, uncertainties, and the robustness of the model, and to aid in decision-making by identifying the range of expected results under different conditions.

In this research, the input parameter which is changed is antecedent dry days. Antecedent dry days refer to the number of consecutive days before a simulation starts when no precipitation occurs. These days are used to simulate the dry weather condition and its impact on the model's initial conditions, such as initial water levels, soil moisture, and pollutant buildup. These initial conditions are used to simulate the state of the system before the simulation starts, and they can have a significant impact on the results of the simulation. The number of antecedent dry days used in a simulation is typically specified by the user in the input data for the model. The hydrology module of SWMM uses Antecedent Dry Days (ADD) method to determine the initial abstraction from the soil. In this research, assessment of four different pollutants by incrementing the ADD from 0 to 40 has been conducted. For each increment, the values of the pollutants were recorded. The chosen pollutants were selected because their event mean concentration, EMC values were high enough to be considered in the assessment. The results of the study were visualized in Figure 4.22, which shows the changes in pollutant levels over the course of the study. This research shows that the Total Suspended Solids (TSS) pollutant level was the most affected among the four pollutants studied. This is evident in Figure 4.22, where a clear trend of increasing TSS levels can be observed with increasing ADD

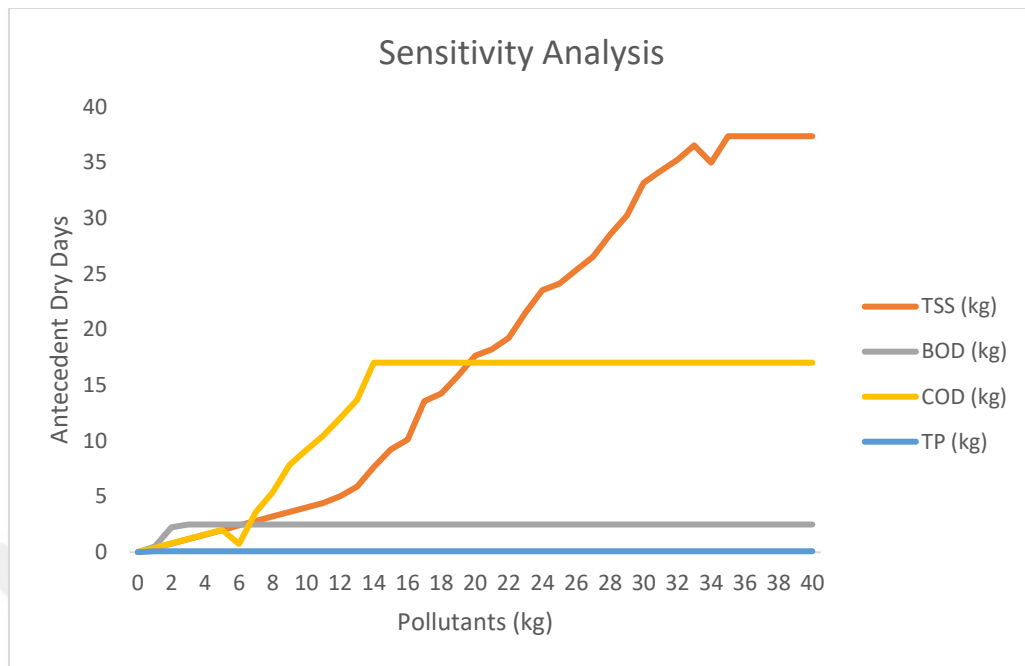


Figure 4.22. Sensitivity analyses of antecedent dry days as variable

One possible reason for this is the higher EMC values of TSS compared to the other pollutants. On the other hand, the levels of the other pollutants remained relatively constant during the initial 2 to 14 days of the study. However, as the number of ADD increased, the TSS values changed drastically. After the ADD were kept at 37 days, there was no significant change in the TSS levels. Therefore, this particular value of ADD is considered safe and was chosen for any further analysis in this research. Over-all, the results of the study indicate that ADD has a significant impact on the TSS pollutant levels and should be taken into consideration when assessing water quality.

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1 Sustainable Stormwater Management Analysis for METU-NCC

After designing the stormwater management network, the next step is to simulate the rainfall. The rainfall considered for this analysis for the METU-NCC Study area is 22 mm/hr., which can be considered as design rainfall intensity in the study area. The simulation of this rainfall will allow us to assess the performance of the stormwater management system in managing the runoff. The first step in the simulation process is to record the volume of runoff generated before the application of LID practices. Once the runoff generated before the application of LIDs has been recorded, the LID practices are applied to the stormwater management network. The simulation of the rainfall is then run again, and the runoff generated after the application of LIDs is recorded. The differences in the results before and after the application of LIDs is clearly visible in Figure 5.1

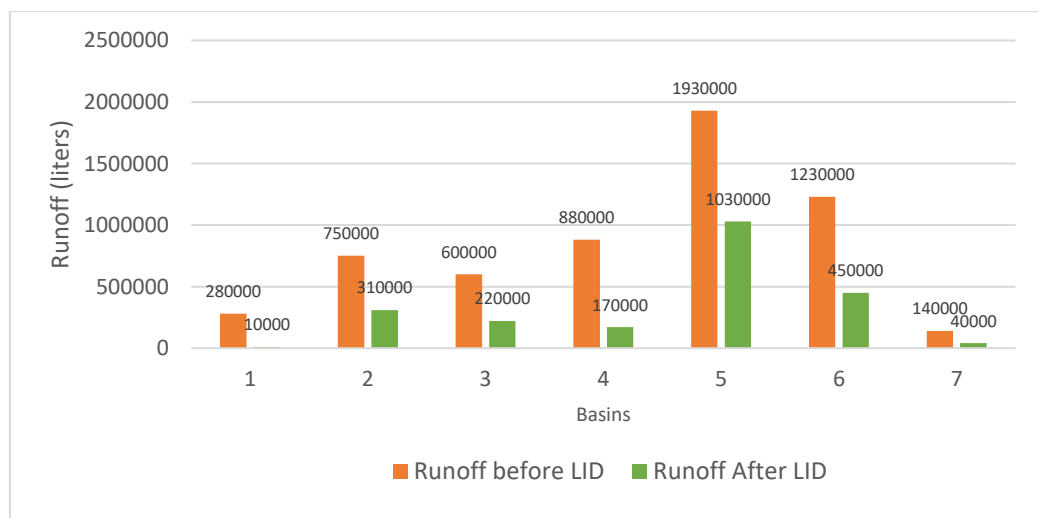


Figure 5.1. Runoff analysis before and after application of LIDs

Figure 5.1 illustrates the reduction in runoff volume that is achieved through the use of LID practices. The image also shows how successfully LID techniques manage stormwater runoff and preserve the environment. It is crucial to keep in mind that the modeling process is not restricted to just one rainfall event and that numerous scenarios can be simulated to assess how well the stormwater management network performs under various rainfall situations. For each basin, the peak reductions are also noted, peak discharges refer to the maximum flow rate of water that is discharged during a storm event. In the stormwater management, peak discharges are important because a discharge which exceeds the peak discharge means there will be urban flooding which can have a significant impact on the environment and infrastructure. Higher than peak discharges can overwhelm the capacity of stormwater systems and lead to flooding in low-lying areas. This can cause damage to property, disrupt transportation and services, and threaten public safety. Another effect of higher peak discharges is increased erosion and sedimentation. Higher peak discharges can cause soil erosion and sedimentation in streams, rivers, and other bodies of water. This can lead to loss of habitat for aquatic species and a decline in water quality. The differences in the peak discharges is visualized using the Figure 5.2. Table 5.1 shows that the Basin 1 had the highest reduction in runoff at 96.42%. This is likely because there are no main roads in the basin, which means that there is no runoff coming from roads. This is an important finding, as it suggests that the runoff in the basin is mainly coming from other sources, such as buildings and parking lots. The study also suggests that the feasibility of applying LID techniques is high in Basin 1. This is because there are pervious areas next to buildings, which gives space for the application of Bioretention Basin (BRBs), and there are buildings next to parking lots, in such conditions the parking lots were converted to Permeable Pavement Systems (PPS), which can treat water not only flowing over the PPS but also from the surrounding buildings.

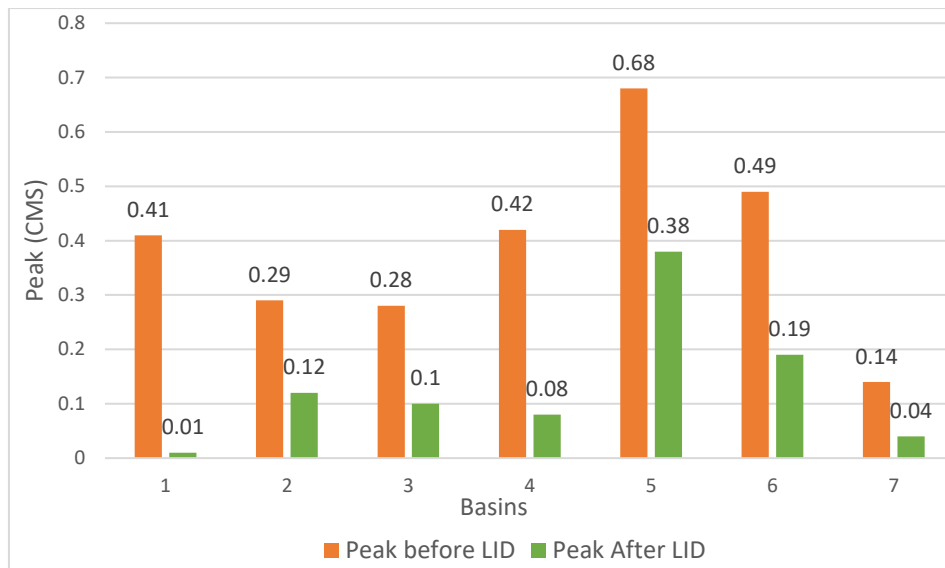


Figure 5.2. Peak discharge analysis before and after LID application

Table 5.1. Percentages reduction in runoff and peak discharges after application of LIDs

Basins	Percent reduction in volume of runoff	Percent reduction in peak discharges
1	96.42	97.56
2	58.66	58.62
3	63.33	64.28
4	80.68	80.95
5	46.63	44.11
6	63.41	61.22
7	71.42	71.42

On average, the chosen LID configuration in the research was able to reduce volume of runoff and peak discharges by 68.65% and 68.31%, respectively. This indicates that the LID techniques used in the study were successful in reducing the amount of runoff and peak values, which can have a positive impact on the

environment by reducing the amount of water that enters into the stormwater system and helps prevent flooding. The total rainfall captured or stored within the METU NCC is shown in Figure 5.3.

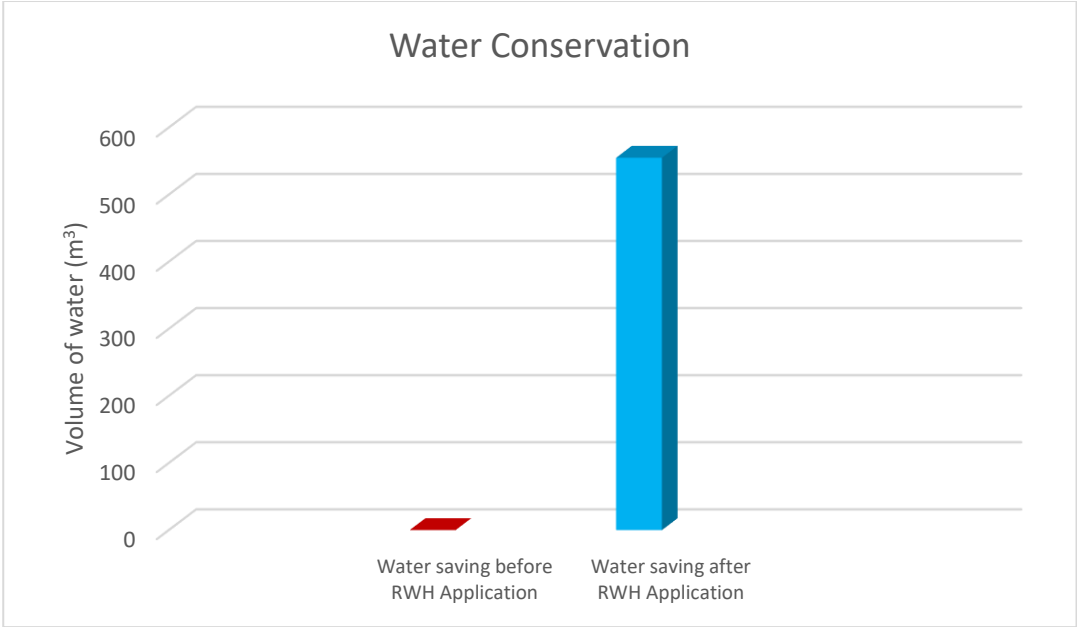
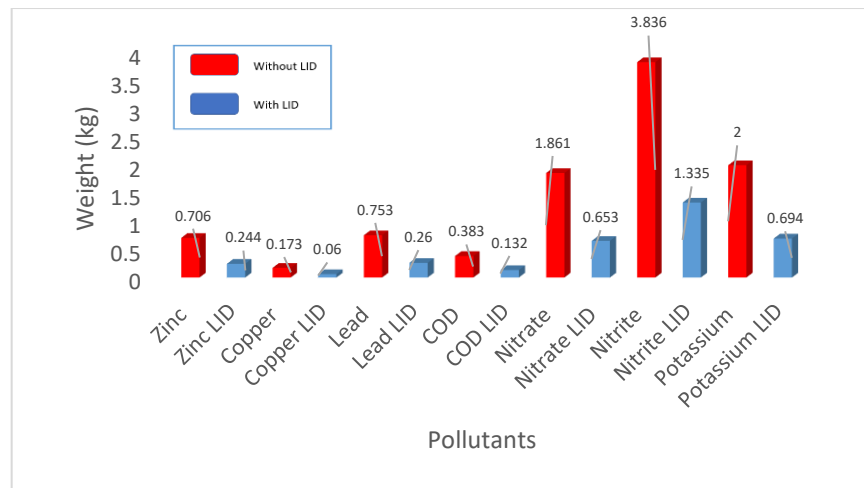
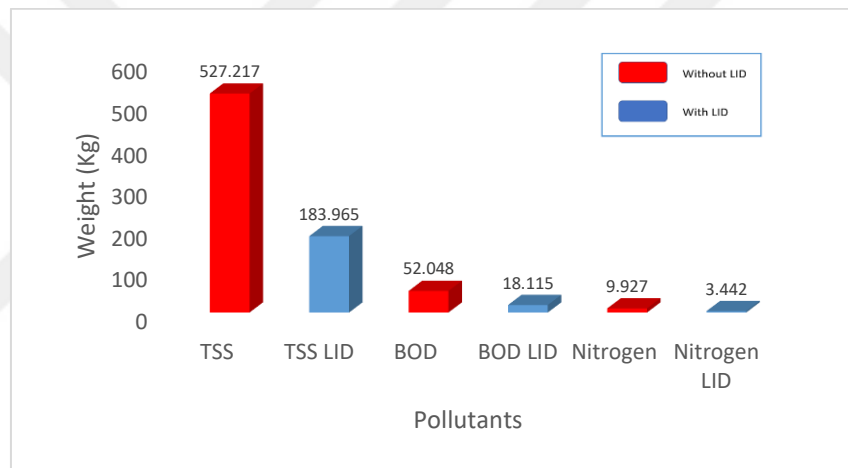


Figure 5.3. Comparison of Water Savings before and after Rainwater Harvesting Implementation

While analyzing the runoff, the pollutant rates were also analyzed before and after application of LIDs, the pollutant considered for this research are mentioned in Table 4.16. The analyses of pollutants are visualized using Figure 5.4 (a) and (b).



(a)



(b)

Figure 5.4. Pollutant analyses before and after application of LID

Figure 5.4 is divided into two groups due to the differences in their scales. The EMC values of TSS is high thus contributing more than rest of the pollutants, overall, there has been a reduction of 65% in the pollutant levels, which is a significant percentage. Pollutant reduction in stormwater can have a number of advantages, both for the environment and for human health. One of the primary advantages is improved water quality in nearby streams, rivers, and other bodies of water. Pollutants in stormwater can be carried into nearby waterways, where they can harm or kill fish and other aquatic life and make the water unsafe for

swimming, fishing, and other recreational activities. Another benefit of reducing pollutants in stormwater is that it can help to prevent flooding and other types of water-related damage. When pollutants build up in stormwater, they can block drainage systems and cause water to back up, which can lead to flooding and other types of damage. By reducing pollutants in stormwater, it can help to keep drainage systems functioning properly, which can help to prevent flooding and other types of damage. In the analysis, the focus was on the context of pollutant reduction, specifically in relation to the values obtained from the pollutant table (See Table 4.17). This table provides the concentrations of pollutants present in each liter of water that flows through the residential area. By implementing LID, we have successfully controlled and reduced the overall volume of runoff. Consequently, this reduction in runoff has led to a proportional decrease in the pollutants per liter.

By implementing LIDs, the rate at which runoff is generated was effectively minimized resulting in less runoff flowing towards the river or stream in the lower areas. As a direct outcome, the concentrations of pollutants in the runoff have also been significantly reduced. Therefore, the reduction in the volume of runoff is directly linked to a decrease in the overall quantity of pollutants present. The findings demonstrate a clear cause-and-effect relationship, highlighting the positive impact of implementing LID strategies. By effectively managing and reducing runoff, this study has achieved a significant reduction in the concentration of pollutants that would otherwise be carried by the runoff. This indicates a tangible environmental benefit, as fewer pollutants are being discharged into the surrounding water bodies. It is crucial to recognize the interconnectedness between runoff reduction and pollutant reduction. By implementing sustainable practices, such as LIDs, we can effectively mitigate the potential negative effects of runoff on water quality. Through the analysis, it is shown that the successful implementation of LIDs not only minimizes the quantity of runoff but also leads to a notable reduction in the concentration of pollutants, ultimately contributing to the preservation and enhancement of our natural ecosystems.

5.2 Green Initiative METU NCC

In the previous results, we observed significant benefits in reducing runoff and peak discharges through the implementation of three LID strategies. However, a key question arises regarding the environmental friendliness of these strategies. To address this, we are planning a green initiative in the campus's future, where we aim to prioritize the application of LID strategies based on their environmental impacts. By assessing and comparing the environmental impacts of each LID strategy, we can determine their relative levels of environmental friendliness. This prioritization will enable us to select and implement the LID strategy that offers the greatest environmental benefits. For this type of analysis to make, the inventory of materials to calculate the emissions from each of them is required.

5.3 Inventory of LIDs for METU-NCC

The inventory of materials used in the construction of LID systems were calculated using the equations shown in the material estimation section, and with the reference of Figure 5.5, which is the configuration used in this research for LIDs which shows detailed information about the dimensions and specifications of the LIDs built on the site of METU NCC. For Rainwater Harvesting, 5 tanks of 2m³ capacity are used. In situations where there was a lack of information, assumptions were made by referring to similar studies conducted by other researchers.

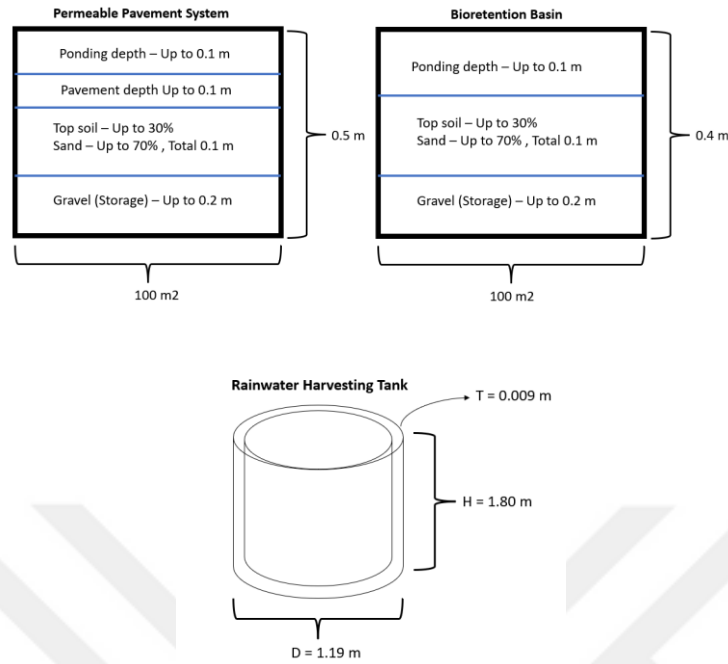


Figure 5.5. Bio-retention, Permeable pavement and Rainwater Harvesting Tank configuration in this research for METU NCC

5.3.1 Functional Unit

Each system's inventory must be normalized for any comparative LCA study in order to compare the impacts to those of other studies of related systems. The functional unit of sustainable construction Studies on LCA have had mixed results. For comparable comparisons, several researchers have employed the functional units "impervious area treated by LID" or "water quality volume treated by LID" [109].

In this study, the aim is to enable a feasible and comparable comparison between three different LID techniques: Bio retention Unit, Permeable pavement, and Rainwater harvesting tank. To achieve this, a common functional unit as the reduction of 10 m^3 of total volume of water is established. To ensure comparability, certain parameters were kept constant throughout the study. The area treated by each of the mentioned LIDs remained constant, as did the rainfall event considered.

These factors provided a consistent baseline for the analysis. Basin 7 in the METU NCC study area was selected as the site for implementing these LIDs. Initially, one of the LIDs were applied, such as the Bioretention basin, and recorded the total volume of runoff generated both before and after the LID's application.

Next, the specifications of the Bioretention basin was iteratively adjusted until achieved a reduction in runoff volume exactly equal to 10 m^3 after the LID's implementation. This process involved a trial-and-error approach to determine the optimal parameters. These steps were repeated for the Permeable pavement and Rainwater Harvesting tank, conducting multiple trials until the optimized specifications were obtained, as presented in Figure 5.5, that resulted in a consistent reduction of 10 m^3 in runoff volume for each LID. By establishing this common goal of a 10 m^3 reduction in runoff volume, the specifications of the LIDs were directly comparable to one another. This allows us to evaluate and compare the environmental Impacts of these LIDs directly.

To inventory the resources, energy and emission flows for all phases of the LID construction, the AGRIBALYSE 3.1 database was used. The inventories include data on materials, transportation, construction, operation, and maintenance. It should be noted that the inventories are not normalized and are specific to the area of construction on the site. The material estimation of all the LIDs is estimated using the equation in the material estimation section, Table 5.2 shows the total material inventory used in this research.

Table 5.2. Material Inventory for LIDs

Materials	BRB/ 100 m² (kg)	PPS/ 100 m² (kg)	RWH/ 5 Tanks (kg)
Gravel	33,600	42,000	-
Sand	11,900	11,900	-
Soil	5,100	5,100	-
Polyethylene High Density granulates	-	-	380

The above quantities are for the manufacturing and installation of 100 square meters of each LID unit. In the production and installation of RWHS systems, no gravel, sand, or silica sand is used. Typically, RWHS tanks are placed underground and require excavation for installation. However, In this case, it is assumed that the tanks will be placed beside the buildings on the surface in order to save on excavation and environmental costs. This is an assumption and the actual installation of the tanks may vary depending on the site conditions and the requirements. The above specifications were only used for the comparison of environmental impact caused by LIDs with each other and is specific to the research area of METU-NCC. For the research area of Guzelyurt district the implementation of LIDs is compared with the implementation of traditional stormwater management technique, which in this case is changing the existing stormwater drainage network with larger diameter pipes to control urban flooding and accommodate more runoff.

5.3.2 Transportation and Excavation Inventory

The choice of transportation method and distance from the production site depends on the availability of local suppliers for the materials. However, it was determined that there is a supplier for rainwater harvesting tank in Turkey. So the materials

required for production of RWH tanks is brought from Turkey in sea transporations as shown in the Figure 5.6. and later it is transported to industrial area in Lefkoşa which is a local supplier and producer of tanks and other materials. It is assumed that the tanks are manufactured by the companies in the industrial area and transported to METU NCC. Similarly, for the sand and gravel transportation, there is a quarry where these materials are mined which is approximately 12 km from the Tufekci Group and from there it is transported to METU NCC about 50 km.



Figure 5.6. Transportation chain of RWH tanks

Similarly, a default distance of 10 km was considered for disposal of debris from the construction site. The excavation and during the construction and disposal phase is assumed to be carried out using hydraulic digger and forklift, all this distances and weights are given as an input to the OpenLCA software for Impact assessment. The details related to distances is represented in Table 5.3.

Table 5.3. Transport and Excavations required in construction and disposal

Process	BRB/ 100 m ²	PPS/ 100 m ²	RWH/ 5 tanks
Transportation by lorry (Kg×km)	7,596,000	9,280,800	38,000
Excavation by Hydraulic digger (m ³)	40	50	-
Forklift operations (hr.)	-	-	1
Transportation by Sea freight (Kg×km)	-	-	87,400
Skid steer Loader (m ³)	40	50	-

5.3.3 Operation Inventory

During the operation and maintenance of Bioretention Basins (BRBs), a machine with 22 horsepower is used twice a year for 1 hour of operation time. The fuel consumption details were obtained from a source [116], and the total fuel consumption over a 50-year lifespan of the BRBs is represented in Table 5.4. For the maintenance of Pressure Protection Systems (PPS), a vacuum sweeping machine with 100 horsepower is used. As the machine is of higher power, it burns more fuel compared to the BRB maintenance machine. The maintenance of Rainwater Harvesting Systems (RWHS) is ignored as there is not much effort required for maintaining an RWHS tank.

Table 5.4. Fuel combustion during O&M of LIDs

Diesel fuel combustion (kg)	BRB /100m²	PPS/ 100m²	RWH/ 5 Tanks
Diesel burned during 22 hp machine operation (kg)	480	-	-
Diesel burned during 100 hp machine operation (kg)	-	2100	-

5.4 Life Cycle Impact Assessment and Comparison for METU - NCC

TRACI v2.1 was used to calculate the LCIA over a functional unit of "10m³ volume of water stored". In ten categories, including ozone depletion, global warming, smog formation, acidification, eutrophication, carcinogenic emissions,

non-carcinogenic emissions, respiratory effects, ecotoxicity, and fossil fuel depletion, the potential for harm is quantified by the midpoint impact assessment method known as TRACI. To determine which LID has the least negative environmental effects, the combined effects of each LID are compared to one another. Figure 5.7, which depicts the overall environmental impact of employing LID systems, compares the complete cradle-to-grave effects of the LID systems. The categories of environmental impacts are presented from left to right, which are ozone depletion (OD) [kg CFC-11], global warming (GW) [kg CO₂, eq], smog (S) [kg O₃, eq], acidification (A) [kg SO₂, eq], eutrophication (E) [kg N, eq], carcinogenic (C) [CTUh], non-carcinogenic (NC) [CTUh], respiratory effects (R) [kg PM_{2.5}, eq], ecotoxicity (ECO) [CTUe], and fossil fuel depletion (FF) [MJ surplus].

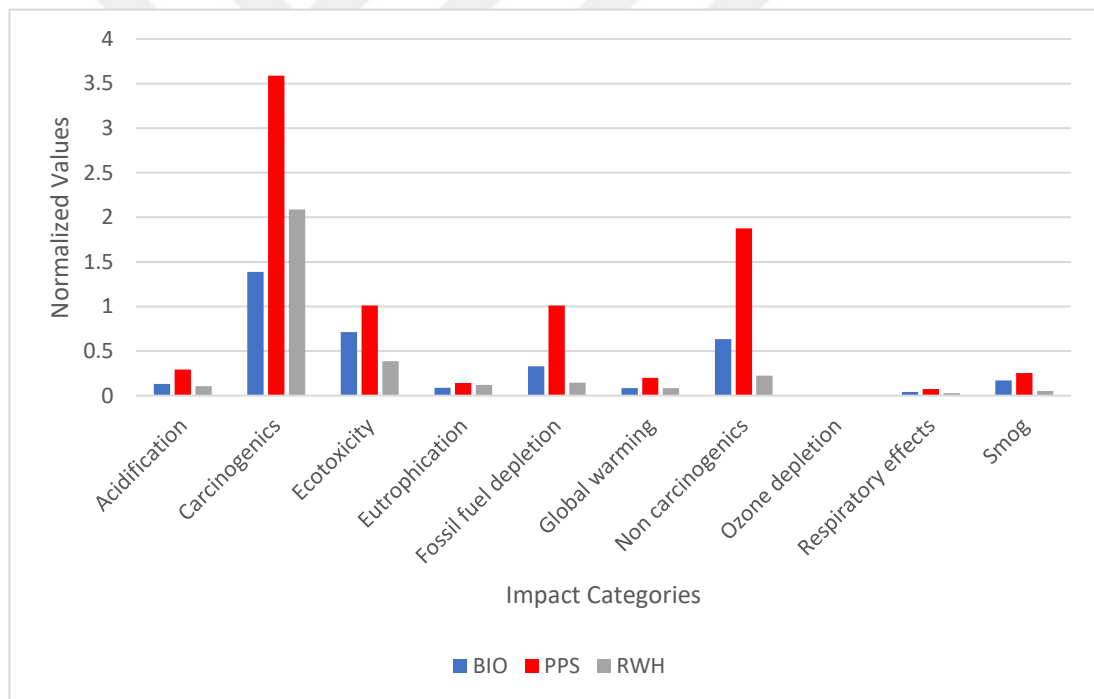


Figure 5.7. Environmental Impacts of LIDs using TRACI 2.1 assessment method

The Relative results are shown in the Figure 5.8, chart shows the relative indicator results of the respective project variants. For each indicator, the maximum result is set to 100% and the results of the other variants are displayed in relation to this result.

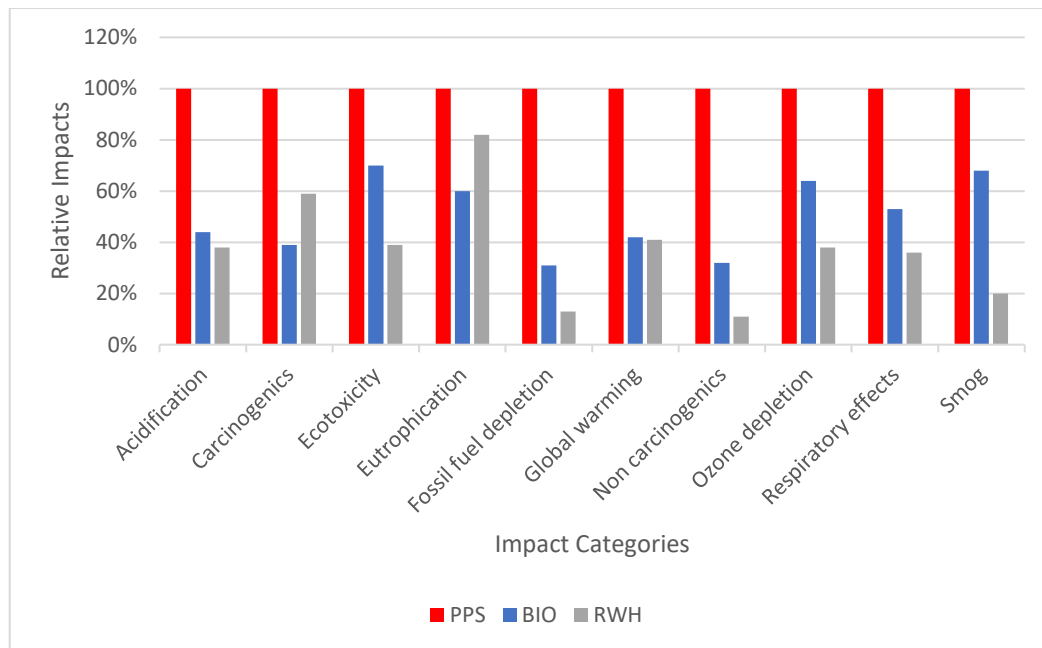


Figure 5.8. Relative results for Impact analysis for LIDs

The Figure 5.7 is the normalised bar chart of the impacts, In this research, the concepts of normalization and weighting within the context of life cycle assessment (LCA) and the OpenLCA software is used. In LCA, normalization involves scaling or transforming impact scores obtained during the characterization phase to a common reference scale. This allows for better comparability and interpretation of the impacts by providing a relative perspective on the magnitude of different impact categories. Additionally, weighting assigns relative importance to these impact categories, considering stakeholders' values and preferences. In this study, "US Canada 2008" set of normalization and weighting factors specific to the United States and Canada during that year has been employed. These factors, based on scientific assessments and expert judgments, enabled to standardize the comparison of different impact categories and make informed decisions regarding environmental priorities based on the specific context of the US and Canada in 2008 [114]. Figure 5.8 provides a clear visualization of the environmental impacts across different categories. Notably, Permeable Pavement Systems (PPS) exhibit the highest impacts in all categories, followed by Bioretention Systems, while

Rainwater Harvesting (RWH) demonstrates the least environmental impacts. Further analysis reveals that RWH slightly surpasses Bioretention Systems in the Carcinogenics and Eutrophication categories. For a more comprehensive understanding of these impacts and their specific values, Table 5.5 presents detailed data. An example of manual calculation of Impacts can be seen in the Appendix section B.

Table 5.5. Impact Category Analysis for LIDs

Impact category	Reference unit	BIO	PPS	RWH
Acidification	kg SO2 eq	12.24769	27.67370	10.01394
Carcinogenics	CTUh	0.00007	0.00018	0.00010
Ecotoxicity	CTUe	7810.12018	11083.40151	4242.29329
Eutrophication	kg N eq	1.80464	2.94770	2.49835
Fossil fuel depletion	MJ surplus	6967.08450	21493.63282	3076.89990
Global warming	kg CO2 eq	2045.93270	4820.13894	2035.44536
Non carcinogenics	CTUh	0.00065	0.00194	0.00023
Ozone depletion	kg CFC-11 eq	0.00035	0.00054	0.00020
Respiratory effects	kg PM2.5 eq	1.17922	2.14625	0.74655
Smog	kg O3 eq	244.69517	366.34090	75.22124

The implementation of permeable pavements, specifically interlocking PPS units, results in higher emissions compared to Bioretention and Rainwater Harvesting (RWH) units. This can be attributed to several factors. Firstly, the production of PPS units requires a larger quantity of materials, particularly gravel and tiles. While the tiles can be reused from excavated existing pavements, the production of gravel involves mining activities that generate higher emissions. The 50:50 ratio of tiles and gravel in PPS unit production contributes to the increased material requirements. Furthermore, the operation and maintenance (O&M) processes associated with PPS units, such as vacuuming and power washing, require a larger amount of diesel fuel compared to Bioretention units. The use of diesel fuel in these processes leads to additional emissions. Additionally, the transportation of

materials, excavation activities, and on-site material mixing for PPS units result in additional emissions.

Due to these factors, PPS exhibit higher environmental impacts when compared to Bioretention and Rainwater Harvesting units. The increased material requirements, including the extraction of gravel and the use of additional diesel fuel during O&M activities, contribute to the higher emissions associated with PPS. It is essential to consider these aspects when assessing the environmental performance of different LID units to make informed decisions regarding their implementation..

In comparison to other LID strategies, the impacts of RWH may seem negligible due to the significant differences in scale. The smaller material usage of RWH units contributes to the perception of lower impacts. For instance, in the comparison of impacts among LIDs, only five 2m^3 RWH tanks are required to store or reduce a volume of 10m^3 of water. On the other hand, LIDs such as bioretention and permeable pavements require approximately 100 m^2 of unit size with a depth of around 0.4 m for each unit to achieve the same water volume reduction. These differences in scale and material usage play a crucial role in the perceived impacts of RWH. The option of choosing a RWH tank wasn't available in the database of Life Cycle Inventory, thus the manufacturing of RWH tank has to be included from scratch. After the production of Polyethylene high density granulates, these materials are later proceeded through injection molding for manufacturing a tank.

When compared to other low impact development strategies such as bio retention basins and permeable pavements, rainwater harvesting tanks have the least impact on the environment. Another main reasons for this are that they require minimal land disturbance and excavation. This is because they can be installed over the ground in this research, and do not require significant modifications to the natural landscape. This is in contrast to bio retention basins which require excavation, grading and modification of natural land-scape. Another reason why rainwater

harvesting tanks have a low impact on the environment is that they require less maintenance. Unlike bio retention basins and permeable pavements, they do not require regular maintenance such as mowing, and they do not require the use of pesticides or herbicides. Additionally, they do not require energy-intensive processes such as mining, crushing, or transporting raw materials. They also do not require large amounts of materials such as soil, sand, or gravel. RWH exhibits higher impacts in two categories, namely carcinogens and eutrophication. These impacts can be attributed to several key factors. Firstly, the production of RWH tanks involves the use of Alkyd paint for coating purposes. The manufacturing process of this paint releases emissions that contribute to the environmental impacts in the carcinogens and eutrophication categories.

Additionally, the transportation of materials plays a significant role in the environmental footprint of RWH. The materials required for the production of RWH tanks are sourced from Turkey and transported to North Cyprus. This long-distance transportation involves multiple methods, including sea freight and transportation by lorries. The increased distance traveled and the need for different transportation modes contribute to higher emissions. Moreover, the production process of RWH tanks, known as injection molding, also contributes to environmental impacts. This process releases a considerable amount of emissions during the manufacturing stage. Furthermore, forklift operations used to position the RWH tanks at their designated locations consume fuel and energy, resulting in additional emissions. Taken together, these factors contribute to the higher impacts observed in the carcinogens and eutrophication categories for Rainwater Harvesting.

Rainwater harvesting tanks also help in water conservation as they can help conserve water by collecting and storing rainwater that can be used later for irrigation or other non-potable uses. In the campus, the water demand is currently met by extracting water from a well located in Guzelyurt town, as illustrated in the accompanying Figure. However, we have identified an opportunity to save a significant amount of water by implementing RWH systems. By installing these

systems, we estimate that we can collect and store up to 555 m^3 of rainwater, which can then be utilized for irrigation purposes. To fully appreciate the environmental benefits of the RWH systems, it is important to consider the alternative scenario in which we solely rely on the Guzelyurt wells to meet the water needs. Extracting water from the wells is a process that demands a substantial amount of energy. Therefore, it is crucial to examine the energy requirements associated with pumping 555 m^3 of water over a distance of 10 km and lifting it to an elevation of 170 m. By conducting a case study on this specific scenario, we can quantitatively assess the energy consumption involved in transporting water from the Guzelyurt wells to the campus. This analysis will help us understand the energy-intensive nature of this process and provide valuable insights into the potential environmental impact

Case Study: Energy Requirement for pumping 555 m^3 of water



Figure 5.9. Pumping Station Guzelyurt

The distance from the Pumping station to METU-NCC is approximately 10 km with an elevation difference of 170 meters including the depth of well and the water level in the well. For this study case following assumptions are made:

Assumptions:

1. The water being pumped is clean water with a density of 1000 kg/m^3 .
2. We will neglect any losses due to friction or inefficiencies in the pumping system.

3. The pumping process is adiabatic, meaning no heat transfer occurs.
4. We will assume standard gravity of 9.8 m/s^2 .

Energy:

To calculate the total energy required for pumping 555 m^3 of water, we need to consider both the potential energy and the kinetic energy.

Potential Energy:

$$\text{Potential Energy} = mgh = (\text{Volume} \times \text{Density}) \times g \times h \quad (18)$$

$$\text{Potential Energy} = 924,630,000 \text{ Joules}$$

Kinetic Energy:

The velocity of the water after being pumped to a height of 170 meters can be approximated as,

$$v = \sqrt{(2gh)}. \quad (19)$$

$$\text{Velocity} = 57.72 \text{ m/s}$$

$$\text{Kinetic Energy} = (1/2) mv^2 \quad (20)$$

$$\text{Kinetic Energy} = 924,518,556 \text{ Joules}$$

$$\text{Total Energy} = \text{Potential Energy} + \text{Kinetic Energy}$$

$$\text{Total Energy} = 924,630,000 \text{ Joules} + 924,518,556 \text{ Joules}$$

$$\text{Total Energy} = 1,849,148,556 \text{ Joules} \approx 1850 \text{ MJ}$$

Thus, using RWH will not only save water but also reduce the emissions which will be caused by pumping operations. This is a significant benefit as it can help mitigate the effects of water scarcity in areas with low rainfall or high-water demand, this is also one of the reasons to select RWHS for this research.

5.5 Sustainable Stormwater Management Analysis For Guzelyurt Town

Subcatchment B has been subdivided into 26 subareas according to the existing pipelines and flow directions. Detailed information regarding the characteristics of each subarea, including area, impervious percentage, characteristic width, and slope, has been compiled and documented in the Table 4.8. Figure 5.10 illustrates a conceptual model representing Subcatchment B.

Various rainfall intensities were examined to determine the maximum intensity that does not result in flooding in junctions and conduits. The outcomes of the different rainfall intensities are presented in Table 5.6. This investigation aimed to identify the threshold at which rainfall intensity exceeds the capacity of the drainage system, leading to potential flood occurrences. By analyzing the recorded data, it was possible to assess the critical rainfall intensity that causes flooding in the nodes. The tabulated results provide valuable insights into the relationship between rainfall intensity and flood occurrences, aiding in the design and management of effective stormwater drainage systems.

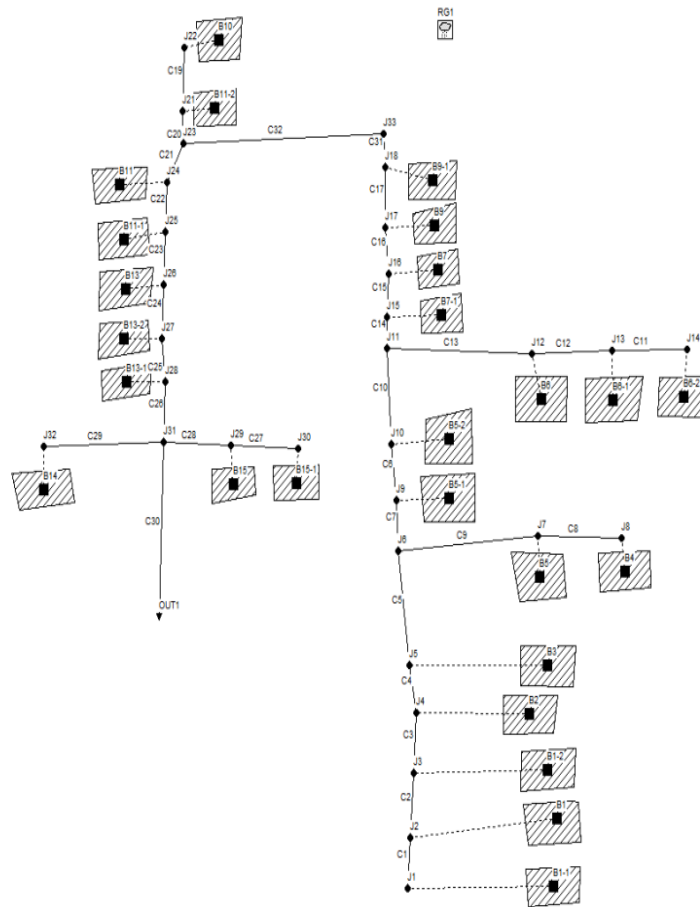


Figure 5.10. Design of Subcatchment B in SWMM

Table 5.6. Flooded nodes under uniform rainfall intensity

Intensity (mm/hr.)	Flooded Junctions	Surcharged Conduits	Outfall Max. Flow (CMS)
26	-	-	0.685
28	J24	C22	0.737
30	J24	C22	0.774
32	J24, J33	C22, C32	0.783
34	J16, J24, J33	C16, C22, C32	0.783
36	J15, J16, J17, J24, J33	C15, C16, C17, C22, C32	0.789
38	J11, J15, J16, J17, J24, J33	C14, C15, C16, C17, C22, C32	0.802

Table 5.6 shows different design rainfalls and its outcomes on the stormwater management network, this analysis is performed by keeping the rainfall intensity uniform throughout the 1-hour duration of rainfall. The objective is to assess the network's performance under varying rainfall intensities and identify the threshold at which flooding occurs. The findings reveal that the stormwater management network experiences flooding when the rainfall intensity reaches 28mm/hr.

In order to further analyze the performance of the stormwater management network, a different approach is taken by simulating a varying rainfall event. This simulation closely resembles real-life rainfall patterns where the intensity changes over the course of one hour. The rainfall intensity is distributed across specific time intervals to create a more realistic scenario. Initially, during the first 15 minutes of the rainfall event, only 10% of the total rainfall accumulates. This represents a relatively lower intensity period. From 15 to 30 minutes, the rainfall intensity increases significantly, reaching a peak at 40% of the total rainfall. This peak

occurs in the second quarter of the rainfall event, resulting in a more concentrated period of heavy rainfall. Following this, the intensity decreases to 30% between 30 to 45 minutes, representing a moderate rainfall period. Finally, in the last segment of the one-hour duration, the intensity drops to 10% until the end. The outcomes of this varying rainfall event analysis are recorded and presented in the Table 5.7 This analysis allows for a more comprehensive understanding of how the Stormwater management network performs under dynamic rainfall conditions.

Table 5.7. Flooded nodes under varying rainfall intensity

Intensity (mm/hr)	Flooded Junctions	Surcharged Conduits	Outfall Max. Flow (CMS)
20	-	-	0.706
22	J24	C22	0.777
24	J16, J24, J33	C16, C22, C32	0.794

The provided tables present an interesting comparison between the constant rainfall intensity and the varying rainfall event. It reveals that the occurrence of flooding was observed earlier in the case of the varying rainfall event compared to the uniform rainfall scenario. This can be attributed to the fact that the peak intensity in the varying rainfall event was reached earlier in 1-hr duration of the rainfall.

In the uniform rainfall intensity analysis, the flooding situation commenced at an intensity of 28 mm/hr., indicating that the stormwater management system could withstand rainfall up to this level before experiencing flooding. However, in the case of the varying rainfall intensity storm event, the flooding occurred much earlier, specifically at an intensity of 20 mm/hr. This implies that the system's capacity to handle rainfall is significantly influenced by the timing and distribution of rainfall intensities. Based on these findings, it can be inferred that the existing Stormwater management system is capable of effectively managing a rainfall event with an intensity of up to 20 mm/hr. This information is valuable for assessing the system's performance under varying rainfall patterns and can guide future

improvements and adaptations to ensure its resilience against earlier and potentially more intense flooding scenarios.

In order to better the effect of LIDs on catchment, three chosen LIDs have been used for this research area. The implementation of LID strategies in the catchment involves a systematic approach that considers the specific characteristics of each sub-area. To ensure optimal performance, the selection of LID measures is tailored to the size of the rooftop spaces in the respective buildings. For buildings with smaller rooftop areas, smaller RWH tanks are installed. These tanks have a capacity that corresponds to the rainfall volume expected from these rooftops. On the other hand, buildings with larger rooftop areas are equipped with larger RWH tanks to accommodate the increased rainfall runoff.

Furthermore, the pavements and parking spaces within the sub-areas undergo a transformation by incorporating permeable pavement systems. These systems allow water to infiltrate through the pavement surface, minimizing runoff and promoting groundwater recharge. In areas where permeable pavement installation is not feasible, such as existing structures or limited space, alternative LID measures like bio-retention units are employed. These units are strategically placed in pervious areas to capture and treat stormwater runoff. The specific details regarding the number of LID units and their corresponding areas can be found in Table 4.11. This table provides a comprehensive overview of the distribution and extent of LID implementation throughout the catchment, ensuring that each sub-area is appropriately equipped with the suitable LID measures based on its unique characteristics and requirements, the results after implementing LIDs is plotted in the Table 5.8.

Table 5.8. Flooding condition after Implementing LIDs under varying rainfall

Intensity (mm/hr)	Flooded Junctions	Surcharged Conduits	Outfall Max. Flow (CMS)
26	-	-	0.220
28	-	-	0.244
30	-	-	0.281
32	-	-	0.335
34	-	-	0.395
36	-	-	0.447
38	-	-	0.543
40	-	-	0.605
42	J24, J33	C22, C32	0.674
44	J24, J33	C22, C32	0.738
46	J15, J16, J17, J24, J33	C15, C16, C17, C22, C32	0.796

The presented table provides compelling evidence of the positive outcomes resulting from the implementation of LID practices. Prior to the integration of LIDs, the stormwater management system was designed to effectively manage runoff from a rainfall event with an intensity of 20 mm/hr. However, after the successful incorporation of LID measures, remarkable improvements have been observed without requiring any modifications to the existing infrastructure of the stormwater management network. The most noteworthy achievement is the significant reduction in the system's load, enabling it to now handle rainfall events with intensities of up to 40 mm/hr. This enhancement signifies a doubling of the system's capacity to manage stormwater without experiencing any instances of flooding. The LID strategies, such as rainwater harvesting tanks, permeable pavements, and bio-retention units, have collectively contributed to this substantial

improvement in the system's resilience. It is noteworthy that these impressive results have been achieved solely through the implementation of LIDs, demonstrating their efficiency in augmenting the existing stormwater management infrastructure.

The primary focus of this study revolves around addressing and mitigating urban flooding. One crucial factor in flood control is the management of peak runoff, as it is directly associated with the occurrence of flooding. Peak runoff refers to the maximum volume of water flowing through a specific area during a rainfall event. When the rate of rainfall exceeds the capacity of the drainage system to effectively manage and convey the runoff, flooding becomes a significant concern to understand, the Figure 5.11 and Table 5.9 below shows the effect of implementing LIDs on peak runoff and % reduction in peak runoff after LID implementation.

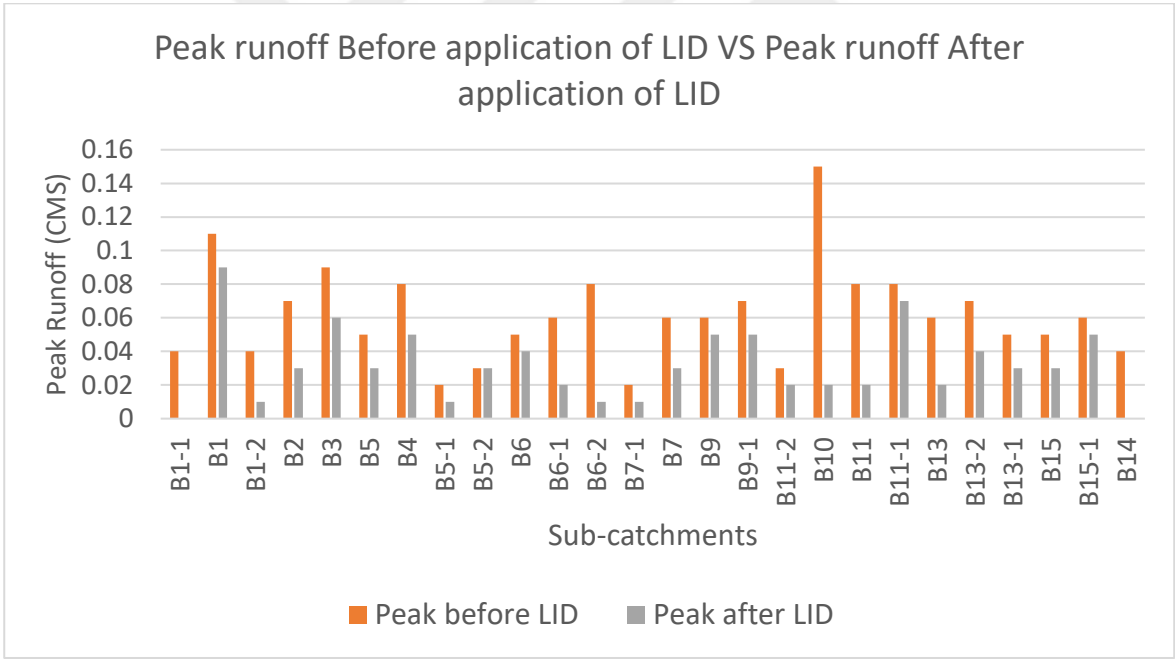


Figure 5.11. Peak runoff reduction after LID implementation

Table 5.9. Percentage reduction in peak runoff

Sub catchments	Reduction of peak runoff (%)
B1-1	-100.00
B1	-18.18
B1-2	-75.00
B2	-57.14
B3	-33.33
B5	-40.00
B4	-37.50
B5-1	-50.00
B5-2	0.00
B6	-20.00
B6-1	-66.67
B6-2	-87.50
B7-1	-50.00
B7	-50.00
B9	-16.67
B9-1	-28.57
B11-2	-33.33
B10	-86.67
B11	-75.00
B11-1	-12.50
B13	-66.67
B13-2	-42.86
B13-1	-40.00
B15	-40.00
B15-1	-16.67
B14	-100.00

5.6 Traditional Storm water Management Approach

In the given scenario, certain conduits in the stormwater management system were identified as problematic, as listed in Table 5.6. To address this issue and enhance

the system's capacity to handle more intense rainfall, modifications were made and are detailed in this section. The objective was to determine the extent to which these modifications could increase the system's conveyance capacity for runoff generated by higher rainfall intensities.

Initially it has been founded that the system could effectively manage runoff from a 20 mm/hr. rainfall event without encountering any issues. However, when the rainfall intensity increased to 21 mm/hr., problems arose in conduits as well as in junctions. As an initial step towards improving the system's performance, the conduit and junctions facing difficulties at the 22 mm/hr. intensity were replaced with larger 0.6 m diameter pipes, and the corresponding junctions were adjusted accordingly. This modification allowed the system to function without problems during a 22 mm/hr. rainfall event.

However, when the rainfall intensity further increased to 24 mm/hr., flooding occurred in conduit C32, C22, and C13. The system did not improve when conduit C32's diameter was increased from 0.5 to 0.6 meters, and conduit C24 developed a surcharged condition. The rainfall intensity was maintained at 22 mm/hr. throughout this iterative process, which was carried out until all of the conduits (C32, C21, C22, C23, C24, C25, C26, and C30) were replaced with 0.6 m diameter pipes. Conduits C15 and C16's sizes were changed at this point in order to evaluate how they might affect system capacity. The results indicated that increasing the diameter of C15 and C16 did not lead to any improvement in handling the rainfall intensity. Instead, the adjacent conduit C17 received the surcharged condition. The intensity was increased to 24 mm/hr. by increasing C17's diameter from 0.5 m to 0.6 m.

The device was able to transfer runoff from a 40 mm/hr. rainfall event without running into any problems after several iterations of this operation. Table 5.10 reports the outcomes of these modifications and lists the conduits that have to be increased to 1 m in diameter in order to handle the particular intensity. It is

important to note that with each modification, the rainfall intensity increased by one step, culminating in the final adjustment that raised the intensity to 40 mm/hr. The table also provides the calculated total length of conduits that required replacement with 1 m pipes, amounting to 800 m, to effectively convey runoff generated from a 40 mm/hr. rainfall event.

Table 5.10. Conduit Resizing using 1 m diameter pipes

Conduits	Diameter Before (m)	Diameter After (m)	Length (m)
C30	0.5	1	60
C32	0.4	1	107.93
C25	0.5	1	85.04
C24	0.5	1	19.72
C23	0.5	1	87.3
C22	0.5	1	58.64
C21	0.5	1	30.48
C26	0.5	1	3.76
C17	0.5	1	50
C16	0.5	1	15
C31	0.5	1	4
C15	0.5	1	35
C14	0.5	1	48.85
C12	0.3	1	53.72
C10	0.5	1	49
C5	0.5	1	21.52
C6	0.5	1	57.52

5.7 Material Inventory for Analysis of Guzelyurt Town

In order to conduct a meaningful life cycle assessment and comparison between LID strategies and traditional stormwater management solutions, it is crucial to establish a feasible and consistent functional unit for comparison. This functional unit ensures that the comparison remains fair and equivalent. To determine the functional unit, we evaluated the maximum capacity of the LID strategies by applying them and assessing their performance. It has been found that the LID measures can effectively handle a rainfall intensity of 40 mm/hr. without causing flooding. This means that the LID systems are designed to manage rainfall events of up to 40 mm/hr. without compromising their functionality. Similarly, the aim is to maintain the same level of performance for the traditional stormwater management solution. To achieve this, the existing piped infrastructure will be replaced with larger pipes, increasing their diameter up to 1 m. Through this upgrade, the system's capacity to handle rainfall events was enhanced and as high as 40 mm/hr.

Therefore, the functional unit of 40 mm/hr. is established as a benchmark for the comparison. This functional unit allows us to evaluate and compare the performance of LID strategies and traditional stormwater management solutions under the same conditions and rainfall intensity. By utilizing this standardized unit, we can effectively assess the feasibility and effectiveness of different approaches and make informed decisions regarding the implementation of sustainable stormwater management systems. A simple Figure shows the different approach and single outcome, which can be seen in the Figure 5.12

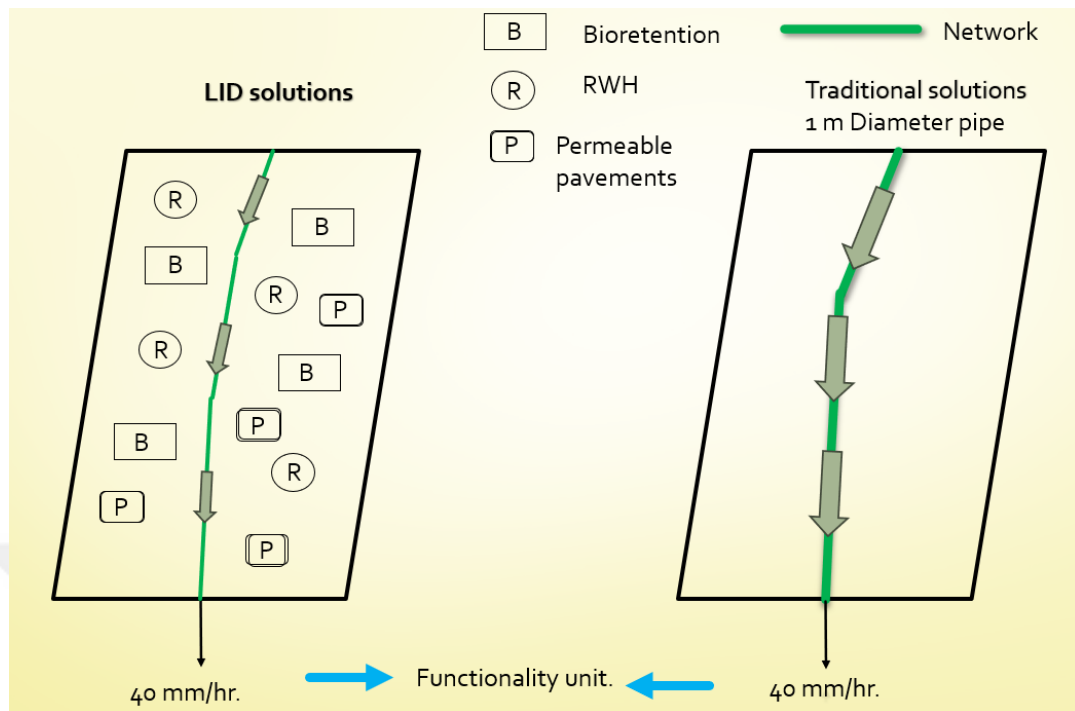


Figure 5.12. Functionality Unit for Comparison

Figure 5.14 illustrates a comparison between the LID solution and the Traditional solution. As previously discussed, the application of LID measures results in an incremental increase in the capacity of the existing stormwater drainage network. By implementing LID strategies, the system becomes capable of effectively managing runoff from a rainfall event with an intensity of 49 mm/hr. This enhanced capacity ensures that the system can handle a higher volume of stormwater and reduce the risk of flooding. This improvement is achieved without the need for extensive modifications to the traditional stormwater management infrastructure.

In contrast, achieving similar results without the application of LID measures would require modifying the traditional system by increasing the sizes of conduits to a diameter of 1 meter. This retrofitting approach aims to enhance the system's capacity to handle runoff from a rainfall event with the same intensity of 40 mm/hr.

To facilitate the Life Cycle Impact Assessment, it is crucial to determine the types and quantities of materials used, as well as the various processes and transportation involved. These inputs can be utilized within the OpenLCA software.

Starting with the material calculations for the LID measures, refer to Table 4.11, which provides the number of units for each LID. Additionally, Table 4.15 offers the necessary specifications for each LID, while Equations 15 and 16 are employed to calculate the materials required. Furthermore, Table 4.16 provides information on the density of the materials. To streamline these details and combine all the relevant materials, we have compiled the following table, as outlined in Table 5.11.

Table 5.11. Total material and processes estimation for all LID's

Materials & Processes	Quantities
Sand (kg)	2,558,500
Gravel (kg)	4,284,000
Excavation (m ³)	7,250
Loader operations (m ³)	7,700,350
Diesel used for O&M (kg)	232,800
Transportation using Lorry (kg*km)	591,447,120
Transportation using Sea freight (kg*km)	25,660,640
Weight of HDPE (kg)	111,568
Forklift operations (hours)	111,568
Injection molding (kg)	111,568

5.8 Material Calculation for Traditional Stormwater Management Solution

In the traditional stormwater management solution, the approach involves resizing the conduits. To implement this solution, it is necessary to excavate the existing stormwater drainage network and install larger conduits with a diameter of 1 meter, covering a length of 800 meters. To determine the materials required for the production of concrete pipes, we consulted Dr. Ceren Ince, and the specific material quantities are documented in Appendix B. Additionally, the volume of the pipes can be calculated using Equation 17. The corresponding amounts needed for the project are presented in the Table 5.12 below.

Table 5.12. Materials required for Concrete pipe production

Materials	Quantity (kg)
Cement	78,218
Coarse Aggregate	335,220
Fine Aggregate	245,224
Water	54,058
Weight of 1 m pipe	906

In order to calculate the materials required for the excavation and construction of the traditional stormwater management solution, it is needed to determine the width of the trench that needs to be excavated. The width of the trench for a 1-meter pipe can be obtained from a reference [113].

The cross-section of the excavation is illustrated in the Figure 5.13 below:

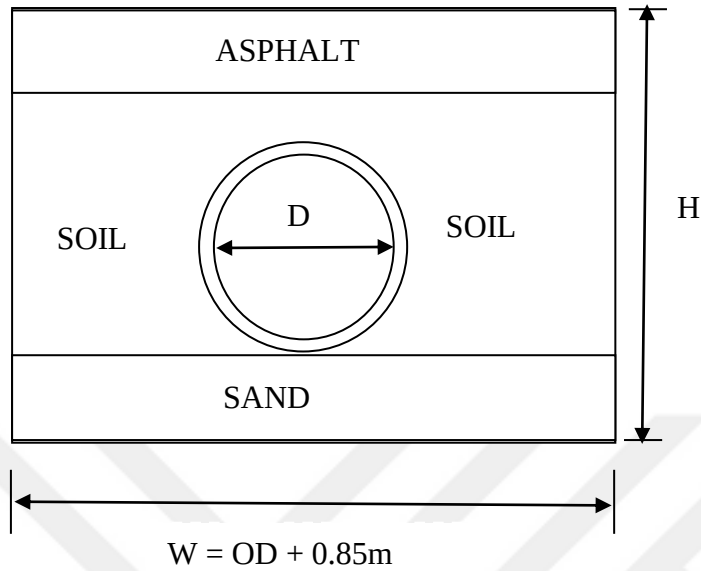


Figure 5.13. Cross-section of Trench

where,

Outer Diameter (OD) = 1.2 m

$W = 2.05$ m

$H = 2$ m

Depth of Asphalt = 0.15 m

Depth of Sand = 0.10 m

According to the specification, materials are calculated along with other processes such as excavation and transportation, the concrete pipe will be transported from Tufekci group from Lefkosa and the cement required will be transported from turkey. The materials are tabulated in Table 5.13.

Table 5.13. Materials required for Excavation

Materials and Processes	Quantities
Sand (kg)	262,400
Asphalt (kg)	602,700
Excavation (m ³)	3280
Loader operations (m ³)	3280
Transportation (kg*km)	85,755,000

All the materials and processes will be added as input in the OpenLCA software and the Life cycle Impact Assessment is carried out.

5.9 Life cycle Impact assessment and comparison for Guzelyurt Town

The OpenLCA software has been utilized to incorporate all the necessary processes and materials as inputs for the life cycle assessment. The analysis is set to take place in Turkey, and the figure below illustrates the inputs that have been included in the system. The Figure 5.14 shows the Inputs added into the software for conducting a LCA, the figure shows the inputs of LID solution, Similarly, for traditional solutions there will be a different set of input list which will be added separately for comparison purposes.

Inputs/Outputs: LID									
Inputs									
Flow	Category	Amount	Unit	Costs/Reven...	Uncertainty	Avoided was...	Provider	Data quality ...	Description
F ₂ Diesel consumption in construction ...	Materials production/Othe...	2.32800E5	kg		none		P Diesel co...		
F ₂ excavation, hydraulic digger	431:Demolition and site pr...	7250.00000	m3		none		P excavatio...		
F ₂ excavation, skid-steer loader	431:Demolition and site pr...	7250.00000	m3		none		P excavatio...		
F ₂ gravel 2/32	Materials production/Othe...	4.28400E6	kg		none		P Gravel 2/...		
F ₂ HDPE granulates	Materials production/Plasti...	1.11568E5	kg		none		P HDPE gra...		
F ₂ Injection moulding (RER) processin...	Others/Ecoinvent cut-off S ...	1.11568E5	kg		none		P injection ...		
F ₂ Maintenance, with forklift truck/FR U	Agricultural/Field Operatio...	130.00000	h		none		P Maintena...		
F ₂ sand 0/2	Materials production/Othe...	2.55850E6	kg		none		P Sand 0/2, ...		
F ₂ Transport, freight, lorry 16-32 metri...	Others/Ecoinvent cut-off S ...	5.91447E8	kg*km		none		P market fo...		
F ₂ Transport, freight, sea, transoceanic ...	Others/Ecoinvent cut-off S ...	2.56606E7	kg*km		none		P transport, ...		

Figure 5.14. Inputs added to LCA Software

Once the inputs have been added, the next step is to create a product system for both the LID and traditional stormwater solution. This involves linking all the inputs and processes to establish a comprehensive system representation. After creating the product system, the subsequent phase involves the comparison of life cycle impact assessments. The results are depicted in the Figure 5.15, where they are presented in a form of normalization bar chart for all ten impact categories of TRACI 2.1.

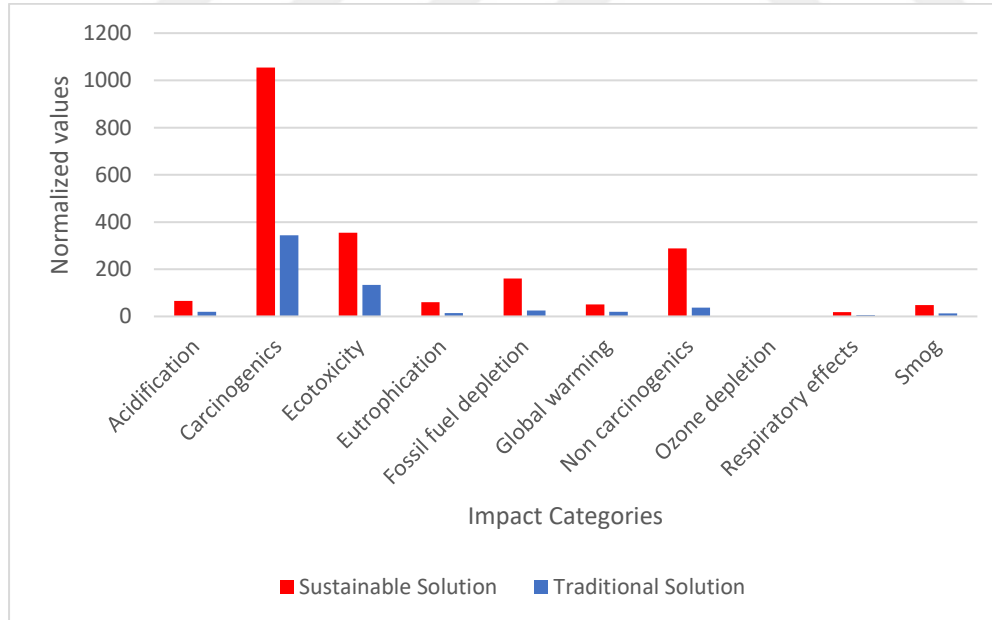


Figure 5.15. Impact analysis comparison using TRACI 2.1

The Relative results are shown in the Figure 5.16, chart shows the relative indicator results of the respective project variants. For each indicator, the maximum result is set to 100% and the results of the other variants are displayed in relation to this result.

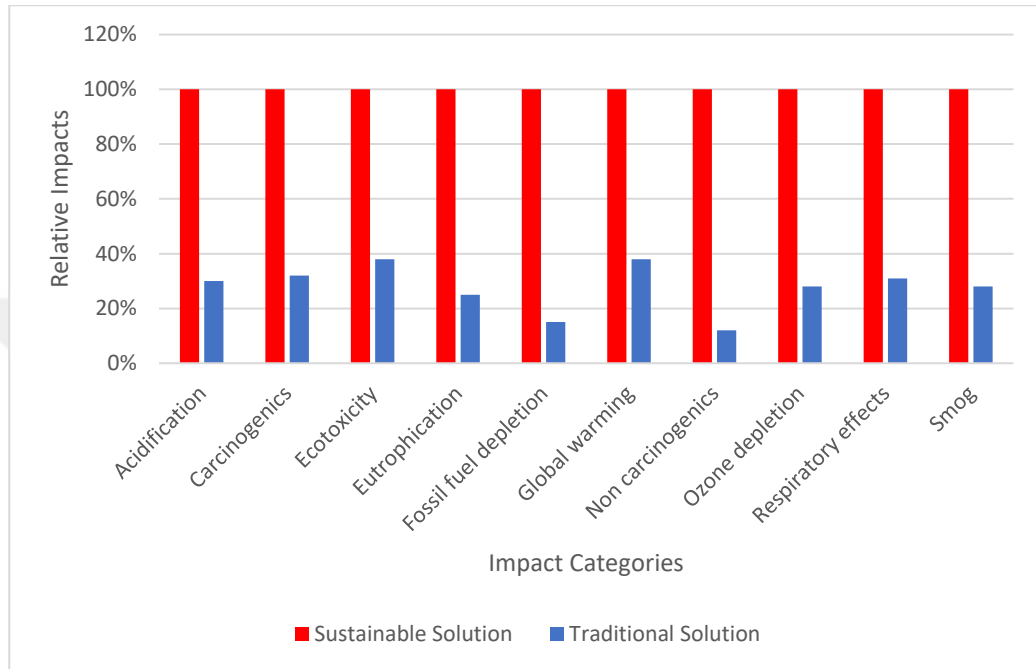


Figure 5.16 Relative results for LCIA for both Solutions.

The analysis of the data reveals that the LID approach exhibits higher environmental impacts compared to the traditional stormwater management solution. This finding can be attributed to several key factors.

Firstly, the construction of LID units requires a greater quantity of materials. This includes the manufacturing of various materials used in LID implementation, which tends to have higher environmental impacts associated with their production processes. In contrast, the traditional stormwater management solution primarily involves the manufacturing of concrete pipes, resulting in comparatively lower impacts.

The higher environmental impacts associated with LID can be further elaborated by considering the life cycle assessment of the respective systems. LID units typically

incorporate multiple components, such as permeable pavements, rainwater harvesting tanks, and bio-retention systems, each requiring specific materials and manufacturing processes. These additional materials and processes contribute to the overall environmental burden of the LID system.

On the other hand, the traditional stormwater management solution focuses mainly on the replacement and installation of concrete pipes. While concrete production does have environmental implications, the overall impact of the Traditional stormwater management system remains relatively lower due to its simplified design and material requirements.

The analysis focused solely on the construction phase may not provide a comprehensive evaluation of the advantages and contributions of implementing LID practices. It is vital to acknowledge the positive environmental aspects that LID solutions offer beyond the initial construction stage.

One notable benefit of LID, such as the utilization of RWH tanks, is its potential for water conservation. By capturing and storing rainwater, LID systems can effectively reduce the demand for fresh water sources. In the specific scenario mentioned, the implementation of RWH tanks enables the collection and storage of 700 m³ of water. This conserved water can be repurposed for various non-potable uses, like irrigation, toilet flushing, or other secondary purposes. By diminishing reliance on conventional water sources, LID solutions contribute to water conservation efforts and promote sustainable water management practices. As the benefits of LIDs such as storing and infiltration of water is not considered in this analysis, these two factors are major environmental benefits which helps in addressing the problem of water storage along with improving the ground water table of the catchment.

Additionally, LID components such as bioretention areas and permeable pavements play a significant role in mitigating urban flooding and facilitating groundwater recharge. Bioretention areas, also known as bioswales, aid in managing stormwater

runoff by filtering pollutants, retaining water, and facilitating gradual infiltration into the ground. This process alleviates stress on the stormwater drainage system and aids in replenishing groundwater resources. Similarly, permeable pavements enable rainwater to permeate through the pavement surface, minimizing runoff and supporting groundwater recharge.

These positive contributions of LID solutions towards water conservation, flood control, and groundwater recharge should be considered when assessing their overall environmental impact. While the initial construction phase may involve higher material usage and associated impacts, the long-term benefits of LID implementation can outweigh these initial drawbacks. It is crucial to conduct a comprehensive life cycle assessment that encompasses the full range of environmental impacts and benefits related to LID strategies, including their operational and long-term effects on water resources and the surrounding ecosystem.

For more detailed overview of impacts the Table 5.14 is drafted which shows the impacts of each category and shows the difference in impact values for both sustainable solution (LID solution) and traditional solution

Table 5.14. Impact categories values for both solutions

Impact category	Reference unit	Sustainable Solution	Traditional Solution
Acidification	kg SO2 eq	6275.11	1913.95
Carcinogenics	CTUh	0.05	0.02
Ecotoxicity	CTUe	3887218.43	1466434.69
Eutrophication	kg N eq	1239.99	304.76
Fossil fuel depletion	MJ surplus	3427955.90	525528.79
Global warming	kg CO2 eq	1222513.43	459857.39
Non carcinogenics	CTUh	0.30	0.04
Ozone depletion	kg CFC-11 eq	0.10	0.03
Respiratory effects	kg PM2.5 eq	547.94	172.54
Smog	kg O3 eq	69843.73	19338.95

From the Figure 5.14, the carcinogenic impact of LID is much higher when compared to other impacts, and from the Table 5.15, thought the values of Impacts of fossil fuel depletion is much higher than the carcinogenic impact but, during normalization of the results the carcinogenic impacts shows higher impacts, The difference in normalized values between the Carcinogenic impact category and the Fossil Fuel Depletion impact category could be due to several factors, one factor is variation in normalization factors, normalization factors used to convert the original values to normalized values may differ significantly between the Carcinogenic and Fossil Fuel Depletion impact categories. The normalization factors are determined based on scientific assessments and expert judgments, and they reflect the relative importance or significance of each impact category within

the specific context of US Canada 2008. If the normalization factor for Carcinogenic impacts is higher than the normalization factor for Fossil Fuel Depletion impacts, it would result in higher normalized values for Carcinogenic impacts compared to Fossil Fuel Depletion impacts. Another possible impact can be, Inherent differences in impact magnitudes, the original values of impact categories are influenced by the specific emissions and resource consumption associated with each category. It's possible that the emissions related to Carcinogenic impacts, such as certain chemical releases, have a higher magnitude in terms of potential harm or toxicity compared to the resource consumption associated with Fossil Fuel Depletion impacts. Therefore, even if the original values for Fossil Fuel Depletion impacts have a higher numerical range, the normalization process may still result in higher normalized values for Carcinogenic impacts due to the underlying differences in impact magnitudes.

5.9.1 Comparative Analysis of Environmental Impacts: Manufacturing, Operation & Maintenance, and Transportation

In this section, the environmental impacts associated with the different stages of LID systems, namely manufacturing and installation, O&M, and transportation were examined. The manufacturing section encompasses the processes involved in the production and installation of LIDs. This includes the manufacturing of LID components and materials, as well as their installation. The O&M section focuses on the ongoing operation and maintenance activities of LID systems. This includes tasks such as mowing the vegetated areas, as well as the use of vacuuming and pressure washing for maintenance purposes. The transportation aspect considers the distances traveled and the modes of transportation used during the various stages of LID implementation. This accounts for the transportation of materials to and from the LID sites. To assess the environmental impacts, we employ the TRACI 2.1 method, which provides a comprehensive framework for evaluating impacts across ten impact categories. The results obtained are then normalized to

facilitate comparison. The findings of this analysis are presented in Figure 5.17, showcasing the absolute environmental impacts of manufacturing, O&M, and transportation processes within the LID context, these results are normalized using US Canada 2008 standards. Additionally, Figure 5.18 illustrates the relative results, highlighting the comparative magnitudes of the impacts across the ten impact categories. Through this comparative analysis, we gain valuable insights into the environmental implications of each stage of LID implementation, aiding in the identification of potential areas for improvement and informed decision-making towards more sustainable practices.

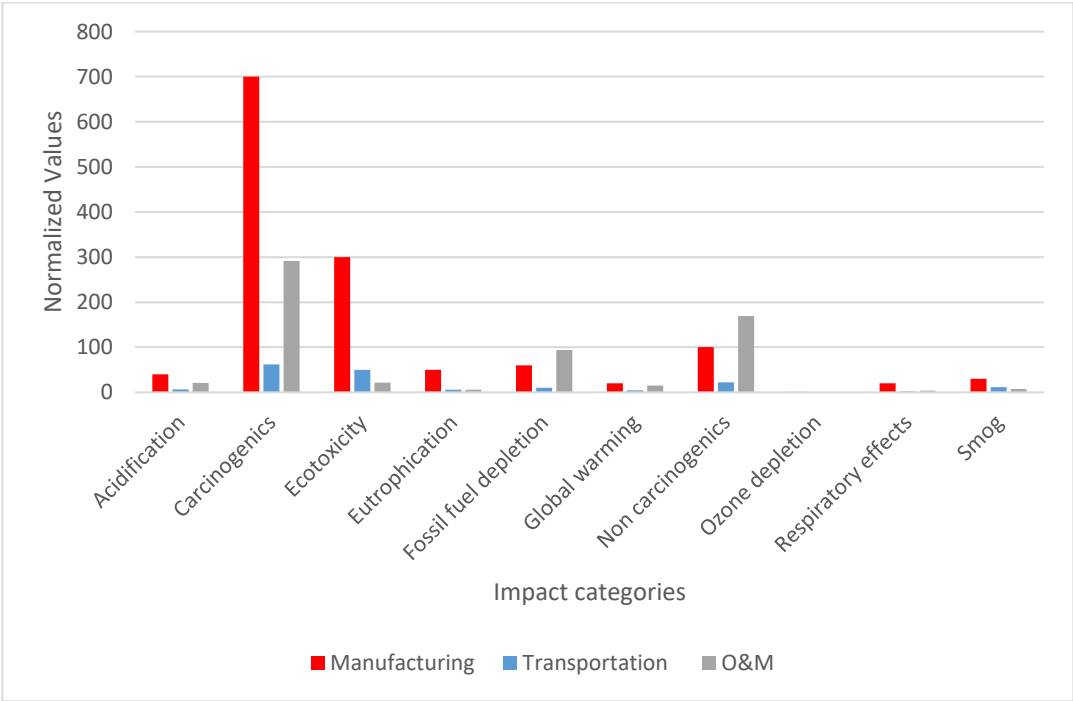


Figure 5.17. Normalized results of comparison of different processes

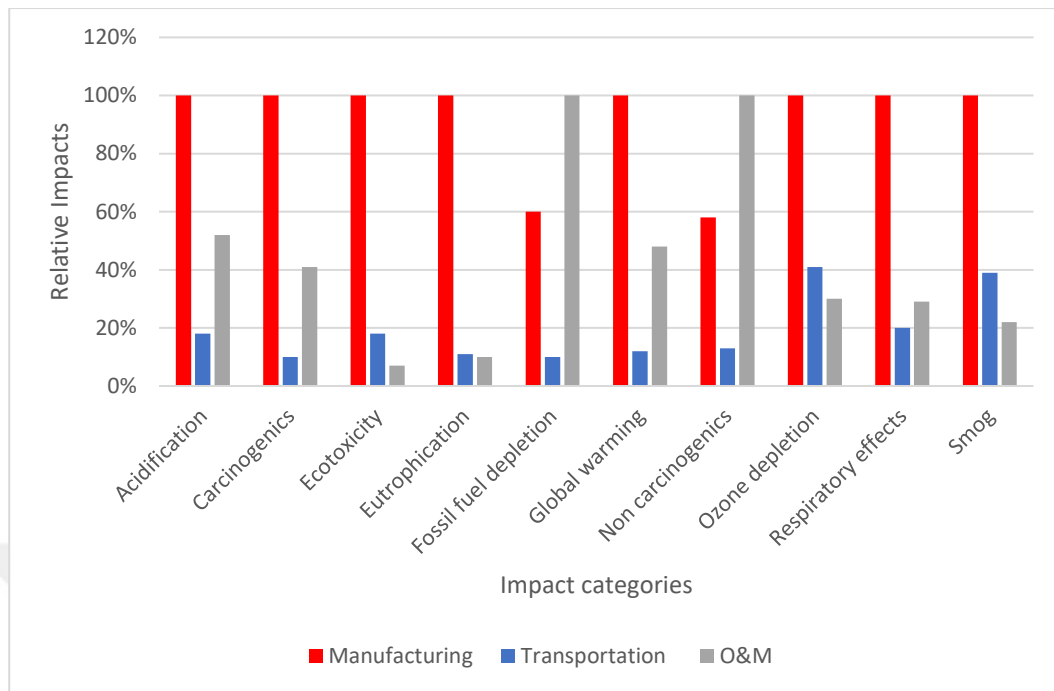


Figure 5.18. Relative results of comparison of different processes

The figures presented above provide a visual representation of the environmental impacts associated with manufacturing, O&M, and transportation processes in the context of LID systems. Among the ten impact categories considered, carcinogenic impacts emerge as the most significant. To provide a more detailed analysis of the impacts, a table has been compiled, outlining the specific impact categories and their corresponding values. This Table 5.15 offers a comprehensive overview of the environmental implications associated with each stage of LID implementation

Table 5.15. Impact analysis results for different processes

Impact category	Reference unit	Manufacturing	O&M	Transportation
Acidification	kg SO ₂ eq	3701.164	1953.257	620.686
Carcinogenics	CTUh	0.035	0.014	0.003
Ecotoxicity	CTUe	3100500.898	235816.569	550900.961
Eutrophication	kg N eq	1006.106	114.063	119.823
Fossil fuel depletion	MJ surplus	1215589.189	1996281.095	216085.612
Global warming	kg CO ₂ eq	766799.825	356707.757	99005.850
Non carcinogenics	CTUh	0.100	0.175	0.023
Ozone depletion	kg CFC-11 eq	0.058	0.018	0.024
Respiratory effects	kg PM _{2.5} eq	368.456	108.273	71.215
Smog	kg O ₃ eq	42880.491	10310.350	16652.884

The relative results depicted in the Figure 5.18 highlight the environmental impacts associated with different stages of LID systems. Upon analyzing the figure, it becomes evident that the manufacturing of LIDs has the most pronounced environmental effects. This can be attributed to the resource-intensive processes involved in LID production. Following manufacturing, the next significant contributor to environmental impacts is the O&M phase. O&M activities, such as mowing and pressure washing, necessitate a substantial amount of fuel consumption, leading to notable impacts in various categories. Specifically, O&M exhibits the highest impacts in fossil fuel depletion and non-carcinogenic impact categories. These elevated impacts result from the increased burning of fuel during maintenance operations. Lastly, transportation contributes to the overall environmental footprint of LID systems, albeit to a lesser extent compared to manufacturing and O&M. The transportation phase encompasses considerations such as distances traveled and transportation modes employed. While transportation plays a relatively smaller role in terms of impacts, it still warrants attention as part of the overall assessment.

The normalization results, as depicted in Figure 5.17, highlight the varying magnitudes of environmental impacts across different impact categories. Notably, the impact category of carcinogenic exhibits the highest values compared to other impacts. This suggests that the manufacturing processes involved in LID production release substances known to be carcinogenic.

To gain a more detailed understanding of the specific processes contributing to these carcinogenic impacts, the Table 5.16 below provides a breakdown of the relevant activities. These activities encompass the manufacturing of LIDs and outline the specific agents or factors associated with carcinogenic emissions. This information enables a focused analysis of the contributing factors and aids in identifying areas for potential mitigation or improvement measures.

Table 5.16. Processes releasing carcinogenic agents

Processes	Emissions (CTUh)
Sand Production	0.022261003
Gravel Production	0.004562103
HDPE granulates production	4.93148E-05
Injection Molding	0.007809236
Excavation	8.70757E-07
Loader operations	1.55322E-06
Forklift operations	4.59328E-08
Alkyd paint production	4.16841E-07
Lubricating oil production	1.70678E-06

The table presented above highlights the various processes that contribute to the carcinogenic impacts within the LID manufacturing context. However, it is important to note that there may be additional processes that also have some level of contribution to carcinogenic impacts, but their emissions are relatively lower and thus not explicitly included in the table. Among the processes listed, sand

sand production, gravel production, and injection molding emerge as significant contributors to carcinogenic impacts. These findings underscore the need for exploring alternative methods and practices that can offer more sustainable alternatives while reducing the associated impacts. Implementing sustainable alternatives in these specific areas of LID manufacturing is crucial to mitigate the environmental risks. For example, exploring the use of alternative materials or production techniques that minimize or eliminate carcinogenic emissions can be a promising approach. This could involve sourcing eco-friendly materials, adopting cleaner manufacturing processes, or utilizing innovative technologies that reduce or eliminate the use of harmful substances. By prioritizing sustainability and actively seeking alternatives, stakeholders in the LID industry can take significant strides towards minimizing the carcinogenic impacts associated with sand production, gravel production, injection molding, and other relevant processes. Such efforts not only reduce the potential risks to human health and the environment but also contribute to the overall sustainability and long-term viability of LID systems.

5.10 Financial Analysis and Cost Comparison of Low Impact Development and Traditional Stormwater Management Solutions

In this section, a comprehensive cost comparison to determine the economic feasibility of various Low Impact Development (LID) solutions for the METU NCC campus is conducted. The costs of different materials required for the LID implementation were obtained through discussions with Mr. Erhan Yengin, the architect of Guzelyurt Municipality, on 16.06.23. The prevailing exchange rate of 23.6 TL/USD on that date was used for the cost calculations. Additionally, the excavation cost, acquired previously, was evaluated using a dollar rate of 18.8 TL/USD. To assess the financial implications of implementing LID solutions, the costs associated with different materials, transportation, and excavation are considered. The Table 5.17 below presents the itemized costs for each component.

Table 5.17. Material and Processes Costs

Materials & Processes	Cost
Sand/ Gravel along with Transportation	500 TL/m ³
Cost of Asphalt	2250 TL/m ³
Labor + Equipment cost of Asphalt laying	1000 TL/m ³
Transportation of Asphalt	2500 TL/13m ³ Truck
Pipe cost Including Transportation	600 TL/1m long pipe, D = 100 cm
Excavation cost with equipment	83.6 TL/m ³

For Rainwater harvesting tank, each tank has different cost based upon the volume of tank, the prices of tanks are given in the Table 5.18, which are all including the transportation.

Table 5.18. Rainwater Harvesting Tank sizes and Costs

Tank Sizes (ton)	Cost (\$)
1	115
1.5	185
2	230
3	450
4	460
5	570
8,5	920
10	1000
15	1340

Based on the data provided in Table 4.15 and Figure 5.5, cost calculations for the implementation of three Low Impact Development (LID) solutions: Bioretention

Unit (100 m²), Permeable Pavement Unit (100 m²), and five Rainwater Harvesting (RWH) tanks (2 m³ each) is performed.

The total cost for each LID solution has been determined as follows:

- The Bioretention system is estimated to cost 18,344 TL (813 USD).
- The Permeable Pavement solution is projected to cost approximately 21,180 TL (942 USD).
- The RWH tanks are expected to incur a cost of 27,140 TL (1,150 USD).

It is worth noting that the cost of RWH tanks is slightly higher compared to the other LID solutions. This can be attributed to the fact that the tank materials are sourced from Turkey and manufactured locally in North Cyprus. Despite the slightly higher cost, RWH tanks offer significant benefits in terms of water conservation and reduced water consumption. These cost calculations provide valuable insights into the financial considerations associated with implementing LID solutions. It enables decision-makers to assess the economic feasibility of each LID option and weigh the costs against the anticipated benefits.

Utilizing the specifications provided in Table 4.15 and the quantity of units outlined in Table 4.11, In this study, cost calculations for both the LID solution and the traditional stormwater management solution have been conducted.

The cost of implementing the LID solution is estimated to be 4,712,104 TL (206,229 USD), while the cost of the Traditional Solution is calculated to be 1,683,208 TL (71,322 USD).

There are several reasons for the higher cost associated with the LID solution. Firstly, LID systems involve the use of various materials, such as bioretention soil, permeable pavement, and rainwater harvesting tanks, each with their respective costs. Additionally, LID implementation requires specialized construction techniques and expertise, which can contribute to higher labor costs compared to the conventional stormwater management approach. Furthermore, the sourcing of

materials and components for LID solutions, particularly for the rainwater harvesting tanks, from external locations can result in increased transportation and import costs.

In contrast, the traditional stormwater management solution primarily involves the replacement and resizing of existing conduits, resulting in a comparatively lower cost. The primary cost driver for the Traditional Solution is the manufacturing and installation of concrete pipes, which are more standardized and readily available. These cost calculations provide valuable insights into the financial implications of adopting LID solutions versus traditional stormwater management methods. By considering the various factors influencing the costs, decision-makers can make informed choices based on the project's budget and the anticipated benefits associated with each approach.

CHAPTER 6

CONCLUSION AND FUTURE WORK

The implementation of LID strategies at METU NCC has proven to be highly effective in reducing runoff volume and mitigating peak discharges, addressing the issue of urban flooding. Among the LID techniques employed, the highest reduction in runoff volume was achieved in Basin 1, reaching an impressive 96.42%. Additionally, the peak reduction of runoff, crucial for flood control, reached a remarkable 97.56% on average across all basins, with an overall average peak reduction of approximately 68%.

One of the significant achievements of LID implementation is the substantial water savings. By employing RWH, a maximum volume of 555m³ of water is saved at METU NCC in a rainfall event of 22 mm/hr. intensity. This not only supports irrigation activities on campus but also reduces the reliance on pumping water from Guzelyurt wells, resulting in an energy saving of approximately 1850 mega joules. The positive environmental impact of LID is further evident through a reduction of pollutant percentages by around 65%, as simulated using SWMM software.

The Life Cycle Impact Assessment (LCIA) conducted as part of the study clearly demonstrates that the implementation of RWH has a lower environmental impact compared to other LID techniques. Considering the Green Initiative at METU NCC Campus.

The combination of LIDs, including Bioretention Basin, Permeable Pavement, and RWH, proves to be a beneficial solution for Guzelyurt town. These LIDs can be implemented without significant disruption to existing infrastructure and have effectively increased the runoff handling capacity of the stormwater management network, enabling it to handle rainfall intensities of up to 40 mm/hr. Prior to the

implementation of these LIDs, flooding occurred even at a rainfall event as low as 22 mm/hr.

The research also explored the traditional stormwater management solution, which involves replacing existing pipelines with larger diameter conduits, by replacing 800 m of existing Storm water Drainage Network of diameter 0.5 m with 1 m diameter concrete pipes will eventually increase the Storm water handling capacity of the system up to 40 mm/hr.

These applications of LIDs in Guzelyurt demonstrated notable reduction in peak discharge, with an average reduction of around 51% at Guzelyurt catchment B, and in some sub-areas, a reduction of 100% was observed.

Comparing the results of the Life Cycle Impact Assessment, it is evident that LID application has a higher environmental impact than the traditional stormwater management solution. To address this, several key approaches can be considered. Firstly, evaluating the materials used in LID manufacturing and utilizing more sustainable alternatives, such as recycled or bio-based materials, can reduce the overall environmental footprint. Secondly, optimizing manufacturing processes through energy and resource efficiency measures can minimize impacts associated with LID production. Additionally, adopting sustainable practices during the operation and maintenance phase, such as reducing fuel consumption and minimizing chemical usage, can further enhance the sustainability of LIDs. Engaging stakeholders and fostering collaboration among manufacturers, designers, regulators, and end-users is crucial for driving innovation and the widespread adoption of sustainable LID practices. Finally, advocating for supportive policies and regulations that incentivize the use of environmentally friendly materials and sustainable manufacturing processes can provide a framework for promoting sustainable LIDs. By implementing these strategies, LIDs can be transformed into more sustainable solutions, minimizing their environmental impacts. The long-term benefits of LID, such as water infiltration

and water savings must also be included as in this research these two factors were not included.

Financial calculations of the LIDs at METU NCC were conducted, revealing that Bioretention was the most economically feasible LID to implement, while RWH offered superior environmental benefits.

In the case of Guzelyurt catchment, LID solutions were more expensive to apply, costing approximately three times more than the traditional solution. LID solution costs about 206,229 USD whereas, Traditional Solution costs about 71,322 USD. It is important to consider both the economic and environmental aspects when evaluating the feasibility of LIDs, as they provide significant long-term environmental benefits.

To advance the findings of this study, future research directions can be pursued to deepen our understanding and application of LID strategies. One crucial avenue is to implement LIDs in real-life urban environments through pilot projects. By constructing and monitoring these projects, it can be directly observed that the performance of LIDs under actual conditions, including their effectiveness in reducing runoff, capacity for infiltration, and ability to mitigate pollutant levels. Comparing these observed outcomes with the simulation results will provide valuable insights into the practicality and reliability of LIDs.

Another important aspect to address is the selection of sustainable materials for LID construction. Research efforts can focus on identifying and evaluating alternative materials with reduced environmental impacts. This may involve exploring the use of recycled materials or locally sourced resources, which can contribute to minimizing the overall environmental footprint of LID implementations. By selecting more sustainable materials, we can enhance the long-term sustainability and resilience of LIDs.

These future research endeavors will not only help validate the effectiveness of LIDs in real-life scenarios but also provide opportunities for improvement and

optimization. By gaining a deeper understanding of their performance and exploring sustainable material options, we can enhance the overall impact and viability of LID solutions in urban stormwater management.



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APPENDICES

A. LID Implementation at Various Basin (METU-NCC)

In this section the LID application at various basins is shown, which was earlier discussed in the Chapter 4 under the Section 4.4.1.



Figure A 1. LID application in Basin 2 (METU-NCC)

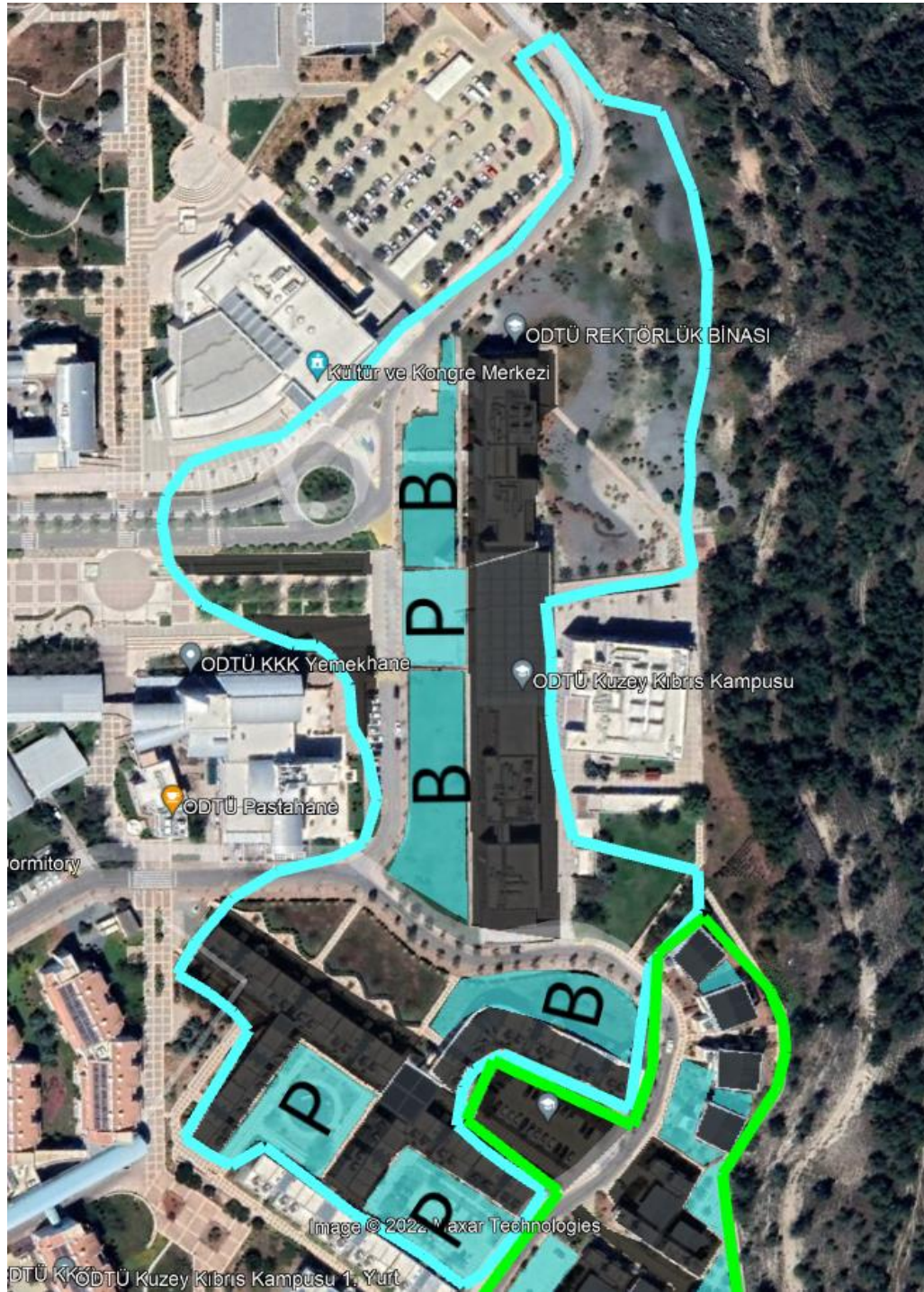


Figure A 2. LID Application In Basin 3 (METU-NCC)

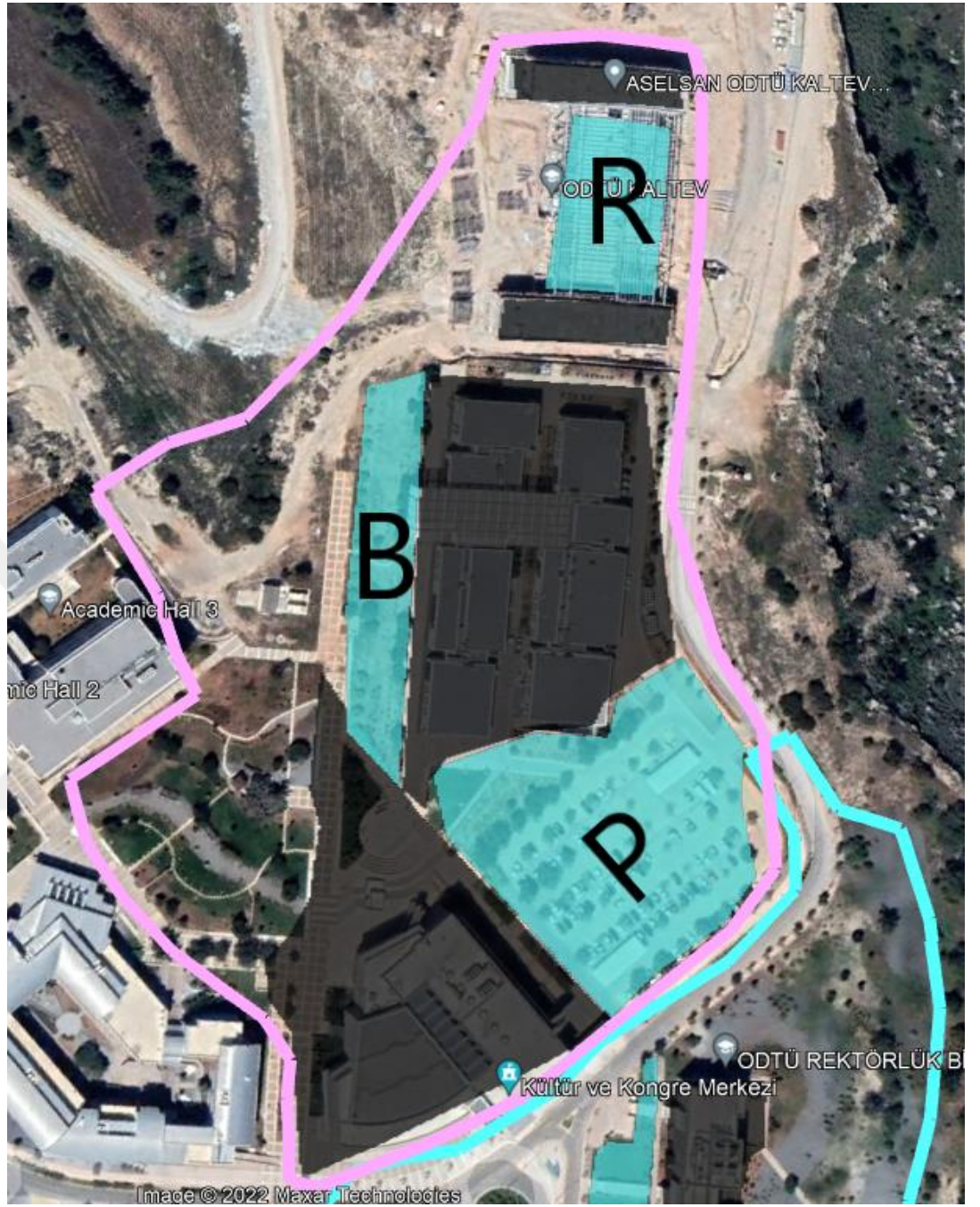


Figure A 3. LID Application in Basin 4 (METU-NCC)



Figure A 4. LID Application in Basin 5 (METU-NCC)



Figure A 5. LID Application in Basin 6 (METU-NCC)



Figure A 6. LID Application in Basin 7 (METU-NCC)

B. Concrete Pipe Material Calculations

Mix design for concrete sewer pipe:

1. Slump = 25-30 mm
2. Maximum aggregate size = 25 mm
3. Water content = 179 kg/m^3
4. Entrapped air (%) = 1.5 %
5. Compression strength at 28 days = 20 mpa
6. Water/ Cement ratio = 0.69
7. Volume of coarse aggregate = 0.69 m^3

$$0.69 * 1600 * 1.005 = 1110 \text{ kg/m}^3$$

8. Volume of Fine aggregate

$$\text{Water} = 0.179 / 1 = 0.179$$

$$\text{Cement} = 0.259 / 3.15 = 0.0822$$

$$\text{Coarse aggregate} = 1.110 / 2.68 = 0.414$$

$$\text{Air} = 0.015$$

By adding the above we get,

$$\text{Total} = 0.179 + 0.0822 + 0.414 + 0.015 = 0.69$$

$$9. \text{Water} = 179 \text{ kg/m}^3$$

$$\text{Cement} = 259 \text{ kg/m}^3$$

$$\text{Coarse aggregate} = 1110 \text{ kg/m}^3$$

$$\text{Fine aggregate} = 812 \text{ kg/m}^3$$

C. Manual Calculation for Finding Environmental Impacts

Case Study: Manual Calculation for finding Environmental Impacts

In this case study, we will find the effect of implementation of Bioretention LID at METU NCC campus, in terms of acidification impact category. The agents which causes acidification and their impact factors which are drawn from the TRACI 2.1 excel workbook are given in the Table C.1 below.

Table C. 2. Impact calculation

Substances	Emissions (kg)	Impact factor (kg SO ₂ eq / kg substance)	Acidification (kg SO ₂ eq)
Ammonia	2.4	1.88E+00	4.51
Nitrogen oxides	9.6	7.00E-01	6.72
Sulfur dioxide	0.4	1.00E+00	0.4

The above Table C.1 gives the information of the amounts of harmful substances which were released which implementing Bioretention LID at METU NCC campus, this amounts of substances are converted to Acidification impacts by multiplying the substances weight with the impact factor given in TRACI 2.1 manual [106].

Thus, the total impact will be obtained by adding the amount in the Acidification column, which sums up to approximately 12 kg SO₂ eq, which is already been calculated by the openLCA software and is mentioned in the Table 5.6.

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YAZARIN / AUTHOR

Soyadı / Surname

BAIG

Adı / Name

MIRZA MOHAMMED ABDUL BASITH BAIG

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M. Baig

Tarih / Date

03/07/23

Tez Danışmanı / Thesis Advisor Full Name:

Assoc. Prof. Berkay Akintoy

Tez Danışmanı İmzası / Thesis Advisor Signature:

Berkay

Eş Danışmanı / Co-Advisor Full Name:

—

Eş Danışmanı İmzası / Co-Advisor Signature:

—

Program Koordinatörü / Program Coordinator Full Name:

Ceren Ince Denger

Program Koordinatörü İmzası / Program Coordinator Signature:

CI