ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

INVESTIGATING THE EFFECTS OF LOW IMPACT DEVELOPMENTS ON URBAN RUNOFF REDUCTION

M.Sc. THESIS

Sina SAMOUEI

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ISTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

DÜŞÜK ETKİLİ GELİŞME YÖNTEMLERİNİN ŞEHİR TAŞKINLARINI AZALTMA ETKİLERİNİN İNCELEMESİ

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Sina SAMOUEI, a M.Sc. student of İTU Graduate School of Science Engineering and Technology student ID 501161511, successfully defended the thesis entitled “INVESTIGATING THE EFFECTS OF LOW IMPACT DEVELOPMENTS ON URBAN RUNOFF REDUCTION”, which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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To my spouse and family, with love.

FOREWORD

First of all I would like to thank my supervisor Assoc. Prof. Mehmet ÖZGER For his helps throughout my graduate studies and his precious advices which was a path finder for me in all stages of this research work.

For her support, love and patience I would like to declare my gratitude and special thanks to my lovely spouse Parastou Ansari and wish her the best.

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May 2019 Sina SAMOUEI

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ABBREVIATIONS

LID **:** Low Impact Development
US EPA **:** United States Environmental Protection Agency
SWMM **:** Storm Water Management Model
ITU **:** Istanbul Technical University
GI **:** Green Infrastructure
GIS **:** Geographic Information Systems
DEM **:** Digital Elevation Model
SCN **:** Stormwater Collection Networks
ISKI **:** İstanbul Water and Sewerage Administration (Istanbul Su ve Kanalizasyon İdaresi)
RMSD **:** Root Mean Square Deviation
EIA **:** Effective Impervious Area

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SUMMARY

In this thesis project the effects of several low impact development (LID) types including green roof, permeable pavement and bio-retention cell on urban flood peak runoff and runoff volume reduction were investigated at Istanbul Technical University main campus using EPA SWMM program.

After literature review in related topics, required data collected and prepared for simulations. These data include university infrastructure data which contains essential information about drainage and sewer systems, the locations of manholes and pipelines and system outfall points, topographical data for the study area with resolution of $\Delta x = \Delta y = 5$ m, soil type and parameters data of the study area, meteorological data which contains the hourly, daily and annual precipitation amounts and the predicted values for 5 storm events with return periods of 2, 5, 10, 25 and 50 years and also the daily temperature data for the period of November 2017 to November 2018.

The land cover map of the study area prepared in Arc GIS program by using the Auto CAD file of the university and also aerial photo of the campus. The land cover map consists of 10 different layers and founded the base of sub catchment parameters calculations, like pervious and impervious %, Manning's roughness and etc.

By using the topographical data, the study area first divided into 5 catchments and after, according to the location of the drainage system inlets and also topography of the area and land cover map, the study area divided to 77 sub catchments. Also the drainage system consists of 196 manholes and 197 conduits and 4 outfall nodes in total.

The main scenario of this study is to replace 5%, 10%, 15% and 20% of the impervious surfaces in the university campus with LID components which mentioned above and investigate the reduction amount in peak runoff and runoff volume. And also by modeling a long term rain fall data (one year), yearly discharge amount from the outfall points of the system will be achieved and in case of constructing a suitable pond, this amount can be use in irrigation and similar purposes.

Dynamic wave routing method for flow routing, and modified Green-Ampt method for infiltration calculations were used in model simulations. The rain data belonging to the storm events were inputted to the model according to normal distribution function and with 10 minutes intervals. The long term rainfall data were inputted as hourly rainfall data for the November 2017 to November 2018 period. And also daily temperature data for the same period were used as an input to the model for evaporation calculations in the model.

For model calibration and validation one rain gauge and meter used for the precipitation and water depth measurements in a manhole located at the outlet of the

study area. The measured and simulated values for the water depth compared with RMSD method and then tried to reduce the difference between measured and simulated values by modifying some parameters of the soil and Manning's roughness. The final accepted parameters were used in the model for simulations.

In this thesis project it is revealed that by replacing 5%, 10%, 15% and 20% of the impervious surfaces of the study area the peak runoff and runoff volume will decrease significantly. For example the maximum peak runoff reduction obtained 38% in simulation with a rain storm with 50 years return period and in case there is 20% LID replacement in the model. Also maximum runoff volume reduction obtained about 35% in the simulation with a rain storm with 50 years return period and in case there is 20% LID replacement implemented in the model.

Also the annual discharge volume for the drainage system obtained as 914,544 m^3 for the period of November 2017 to November 2018 which in case of constructing a suitable pond can be use in irrigation or similar purposes.

DÜŞÜK ETKİLİ GELİŞME YÖNTEMLERİNİN ŞEHİR TAŞKINLARINI AZALTMA ETKİLERİNİN İNCELEMESİ

ÖZET

Su! Hayatın belki en önemli faktörüdür ama bazen biz insanlar adımız dan da belli olduğu gibi bu nimetin nekadar önemli olduğunu unuturuz, yer küresindeki su kaynaklarını boşa harcar uzaydaki başka kürelerde su ararız!

Insanların su ve doğayla olan ilişkisi hernekadar da kitaplarda ve bilim merkezlerinde vurgulanıp doğrusu öğretilsede ne yazıkki gerçek hayatta bir çok yanlışlıklara maruz kalmıştır ve bu nedenle şimdi veya gelecekte bir çok sorunlar yaşayacaktır. Insan toplumlarının zamanla büyümesi ve dolaysıyla ihtiyaçlarının artması, köylerden büyük şehirlere göç etme veya köylerde kentleşmeye yol açmıştır.

Kentleşmenin temel faktörlerinden olan zemin değişmesi doğanın yeşil ve canlı örtüsünü aradan kaldırıp yerine sert ve cansız metal ve asfalt gibi örtüleri yerleştirmiştir bu nedenle yağmura karşı zeminin su ğeçirimliliğini azaltmış ve hatta engellemiştir. Alt tabaka toprağa geçiş yolu bulamayan yağmur, yüzeysel akışlara çevirilip ve şiddetli yağmur zamanlarında su baskınlarına yol açıyor.

LID veya Low Impact Development adıyla tanımlanan yöntemler günümüzde Amerika Kanada ve Avropanın gelişmiş olduğu ülkelerin çoğunda uygulanmakta olup ve doğayı daha az etkileyerek kentleşme teknikleri sunmaktadır. Türkiye gibi gelişmekte olan ülkeler, gelişmiş olan ülkelerden daha hızlı büyüme yaptıkları için LID stratejilerinin uygulanmasına daha çok ihtiyaç duymaktadırlar. Buna ilaveten sürdürebilir büyüme gelecekteki refah ve kalkınmanın hızlı ve güvenilir geçişi için önemli rol oynamaktadır.

Bu tez projesi kapsamında kentleşmiş bir bölge örneği olarak Istanbul Teknik Üniversitesi farklı LID denemeleri için kullanılmıştır. Ayrica üniversite yetkililerinin dediklerine göre 2009 ve 2011 yıllarında kampüsün güney bölgesinde şiddetli yağmurlardan dolayı bir kaç binayı su basmış ve bu nedenle maddi hasarlar meydana gelmiştir. Bu yüzden LID stratejileri kullanılarak üniversite kampüsünde farklı dönüş aralıkları olan 5 fırtına için yağış akış modeli yapılıp pik debi ve akış hacmi azalması incelenmiştir.

Söz konusu olan LID denemeleri bu projede 3 bileşenden oluşmaktadır: 1- Yeşil Çatı 2- Su Geçirebilir Zemin ve 3- Bio Biriktirme Bahçesi. Bu tez çalışmasında, araştırma alanı olan Istanbul Teknik Üniversitesine ait su geçirmeyen yüzeylerinin, 5%, 10%, 15% ve 20% si, adı geçen LID bileşenlerile değiştirilerek pik debi ve akış hacmi azalması farklı fırtınalar için test edilmiş ve sonuçları rapor edilmiştir.

Bu projede US EPA, “American Environment Protection Agency” nin SWMM, “Storm Water Management Model” uygulaması kullanılmıştır. Ayrıca GIS le ilgili olan hesaplamalar Arc GIS programıyla hazırlanmıştır.

Model oluşturmak için öncelikle literatür araştırması yapılmış ve sonra araştırma bölgesi olan Istanbul Teknik Üniversitesine ayit datalar toplanmıştır.

Yağmur suyu drenaj hatları ve detayları, binalar ve fakültelere ayit olan detaylar, otoparklar ve yolları gösteren harita Auto CAD file halinde Üniversite Yapı İşleri Müdürlüğinden temin edilimiştir. Ayrıca data ların ve su rogarlarının konumlarının doğru olduğundan emin olmak ve bazı kayıp rogarları tespit etmek için saha kontrolleri yapılmıştır. Üniversite kampüsünün sadece batı kısmının Altyapı dataları mevcut olduğundan model yapımında toplam da 1,08 km^2 alana sahip olan batı kısmı hesaba alınmıştır. Bu harita alt katman olarak land cover haritası oluşturmak için kullanılmıştır. Mevcut yeşil alanlar ve diğer belirsiz olan alanlar Arc GIS programıyla uydu görüntüsü kullanarak tesbit edilip land cover haritasına eklenilmiştir.

Toplam 10 katman dan oluşan bitki örtüsü haritasında asfalt alanlar, binalar, havuzlar, otoparklar, çimenlikler, taşlı yüzeyler, ağaçlık alanlar, taş döşeme alanlar, orta ağaçlık alanlar ve gölete ayrıca yer verilmiştir ve her birinin fiziksel özellikleri tek tek hesaplanmıştır.

Meteorolojik datalar ise gözlenen saatlik, aylık ve yıllık bazda yağmur şiddeti ve hacmi, günlük maksimum ve minimum hava sıcaklığı ve beklenen en büyük yağışlar 2, 5, 10, 25 ve 50 yıllık dönüş aralığı için Meteoroloji Genel Müdürlüğü' nden Sarıyer istasyonu için talep edilerek temin edilmiştir. Sarıyer istasyonu araştırma bölgesine en yakın istasyon olduğu için seçilmiştir.

Bu modelde vaka bazlı 2, 5, 10, 25 ve 50 yıllık dönüş aralığı olan fırtınalar için 5 simülasyon yapılmıştır ve pik debi ve akış hacmi değerleri LID uyguladıktan sonra ve LID uygulamaksızın elde edilip karşılaştırılmıştır. Ayrıca drenaj hattının, bir yıl içinde tahliye ettiği su miktarını elde etmek için Kasım 2017 den Kasım 2018 e kadar bir yıllık saatlik yağmur datası modele girilerek uzun zamanlı model yapılmıştır ve değerleri elde edilmiştir. Sonuç kısmında açıklanmış olan bu su miktarı drenaj ana çıkış noktasında uygun bir biriktirme havuzu yapılarak tasarruf edilip sulama gibi amaçlarda kullanıla bilir.

Bu projede topografi datası araştırma bölgesi için $\Delta x = \Delta y = 5$ m çözünebilirliği ile temin edilmiştir böyle yüksek bir çözünebilirliği olan data kullanmakla daha doğru ve gerçeğe yakın sonuçlar almak amaçlanmıştır. Toprak datası için önceki araştırmalardan elde edilen değerleri referans vererek kullanılmıştır.

Araştırma alanı Arc GIS programı ve topografik data kullanılarak önce 5 havzaya bölünmüştür ve sonra her bir havza su giriş rogarlarının konumu, topografik data ve yüzey türünü göz önünde bulundurarak toplam da 77 althavzaya bölünmüştür. Ayrıca araştırma alanına ayit olan 196 manhole ve 197 boru drenaj systemi modelini oluşturmak için hesaba alınmıştır.

Bu çalışmada yapılmış olan yağış-akış modeli SWMM programının Dynamic Wave Routing seçeneğile incelenmiştir bu nedenle bacaların dolması ve taşması, borulardaki basınçlı akış ve ters yönlu akışlar da hesaba alınmıştır. Ayrıca zemine sızma hesaplama yöntemi olarak Modified Green-Ampt yöntemi kullanılmıştır bu yöntem, önce hafif başlayan ve sonra şiddetlenen fırtınalarda toprağın yüzeyindeki rutubet boşluğunu çabuk tüketmiyor kabulü ile ve ilk aşaması uzun süren ve yağış şiddeti toprağın doygun koşullardaki hidrolik iletkenlik değerinden daha az olan fırtınalarda gerçeğe daha yakın bir sonuç almak için kullanılmaktadır.

LID control bileşenlerini yerleştirmek için önce yağış akış modeli incelenmiştir. Fırtına esnasında su baskınlarına uğrayan ve durumu daha kritik olan alt havzalar belirlenmiştir sonra alt havzanın hangi LID bileşenine uygun olması incelenerek yerlerine karar verilmiştir. Toplamda kampüsün su geçirmez zeminlerinin 5%, 10%, 15% ve 20% si kademeli olarak LID bileşenlerile değiştirilerek model terkar incelenmiştir ve pik debi ve akış hacmindeki azalma oranları elde edilmiştir.

Bu proje çalışmasında bir yağmur ölçer aleti kullanılarak bir yağmur yağışı kalibrasyon ve validasyon amacı için 15 dakika aralıklarla ölçülmüştür. Aynı zaman da kampüsün güneyinde yer alan bir birleşim noktasından (baca) su seiyesi ölçülmüştür. Aynı nokta için model de çıkan su seviyesi elde edilerek ölçülen seviye ile karşılaştırılmıştır. RMSD yöntemile aradaki fark elde edilmiştir ve bu farkı azaltmak için zemin parametrelerinde modifikasyon yapılmıştır. Sonuç olarak en iyi RMSD değeri 10,35 mm elde edilmiş ve kalibre olunmuş parametreler simülasyon da kullanılmak üzere modele girilmiştir.

Elde edilen sonuçlara göre kampüsteki su geçirmez yüzeylerin 5%, 10%, 15% ve 20% si 4 kademede bahsetmiş olduğumuz 3 LID bileşeni olan: 1- Yeşil Çatı 2- Su Geçirebilir Zemin ve 3- Bio Biriktirme Bahçesi ile değiştirdiğimizde pik debi ve akış hacmin de önemli azalmalar meydana gelmiştir. Sonuçlar arasında runoff peak flow ya ayit en çok azalma 38% ile 50 yıllık dönüş aralığı olan fırtına ve 20% LID uygulaması durumunda kayd edilmiştir.

Aynı şekilde akış hacmi azalmasına ait olan sonuçlarda ise en büyük azalma 34.93% ile 50 yıllık dönüş aralığı olan fırtına ve 20% LID uygulaması durumunda kaydedilmiştir.

Ayrıca drenaj hatlarının bir yıl içinde nekadar yağmur suyu tahliye ettiğini elde etmek için kasım 2017 den kasım 2018 e kadar olan saatlik yağmur verisi ve aynı zaman dilimi için buharlaşmanı hesaba katmak için günlük sıcaklık verisi modele girildi. Bir yıllık simülasyon sonun da drenaj hatlarından toplam 914,544 m^3 su çıkış yaptığı elde edildi. Bu miktar su drenaj sisteminin ana çıkış noktasında uygun bir birikyirme havuzu yapılarak tasarruf edilip ve sulama gibi amaçlar için kullanılabilir.

1. INTRODUCTION

1.1 General:

Rapid development of human societies and cities during centuries and decades is a familiar issue for all people around the world specially engineers. Urbanization may be seem a deceptive issue at the first look but unfortunately has its own harms and side effects. Regarding that most common materials for constructions are steel, concrete and stone because of their high resistance ability against different forces most of the buildings and surfaces builds by them. These high resistance materials have a very less permeable ability and some of them even don’t have any voids for conducting water through.

By expanding the cities all over the world more natural surfaces replace with these impervious materials. Decreasing the soil type surfaces, wooded areas, grasslands and wetlands in one side and replacing them with asphalt, concrete and steel on the other side can cause serious problems related with rain water and storm runoffs drainage.

Additional to the excessive land cover modifications occurring in the cities and urban areas, we are facing severe weather conditions due to climate change. As a matter of fact, now we have complicated problems in our cities by combining the climate change effects and land cover modifications at the same time (Rosenberg et al. 2010; Hanak and Lund, 2012). This condition emphasizes the importance of finding a solution for urban drainage systems and dictates the changes must be done for traditional sewer systems implemented in our cities already.

One of the best responses to the critic situations of our growing cities can be giving back the ability of absorbing rain water to the modified land. This could be resemble as increasing the green area ratio of the land or some other technics like building retention ponds, infiltration trenches and bio swales. This collection of solutions can be identified as a concept named Low Impact Developments (LID) which is commonly used in U.S, and Canada (Ahiablame et al. 2012; Liu et al. 2016).

The Low Impact Development (LID) is an alternative approach for traditional stormwater drainage system with and objective for reaching sustainability in the urban areas. (Dietz, 2007). LIDs are smart development tools engaging Green Infrastructures (GI) like: green roofs, permeable pavements, retention swales, rain barrels and etc. for reducing the flood risk and water pollutants. The main issue and problem for using and examining their performance is how to model them with respect that there are very complex interactions between water movements and urban elements and also complex Stormwater Collection Networks (SCNs) (Kaykhosravi, 2018).

United States Environmental Protection Agency (US EPA) has developed a program named: Storm Water Management Model (SWMM). A dynamic Hydrology-Hydraulic simulation model which is used for modeling single event or long term events simulation of water quantity and quality especially used in urban areas. This program additional to the ability of modeling the rainfall runoff process in urban areas is a good appliance for modeling LID implementation and evaluate their performance within the urban catchments (Rossman, 2015).

Istanbul is a major and populated city in the Marmara region of the Turkey. It is Turkey’s economic and historic center and with a population of over 15.000.000 it is the most populated city of the country. Like many other major cities in the world Istanbul also has been affected by the rapid urbanization since centuries and also exposed to many devastating storms during centuries.

In this study tried to provide a good example of LID implementation and its effects on urban stormwater reduction in Istanbul Technical University where according to the authorities had experienced a sever inundation in some parts at a storm event in 2009, and with hope of extension of these strategies to other parts of the city in the future.

1.2 Purpose of Thesis:

The main purpose of this thesis at the first place is creating a high resolution land cover map of the study area and then providing a rainfall-runoff and flow routing model for simulating the implementation of combination of three kind of LID practices including Green roofs, Permeable Pavements, Bio Retention Cells, in four replacement percentages of 5%, 10%, 15% and 20% by using EPA SWMM 5.1 rainfall runoff modeling program, and evaluating the effects of this kinds and percentages of LIDs on runoff peak flow and runoff volume reduction under five different rain storm events with the return periods of 2, 5, 10, 25 and 50 years.

And additional purpose of this research work is to simulate a long-term rainfall data starting from November 2017 to November 2018 to obtain approximate annual discharge volume from drainage system outfall points. This volume of discharged water can be save by constructing a suitable retention pond at the outfall point of the drainage system and use for irrigation or similar purposes in the future.

This thesis is the result of researches and hard work by consuming noticeable time and field investigations and written with hope that will be a useful reference for future studies.

1.3 Literature Review

By growing urbanization and expansion of cities all over the world the ratio of impervious surfaces in urban areas are increasing and as a result we are facing with several problems related with inundations in cities and urban areas.

Urbanization turn to a novel environmental issue with growing the population of cities by time. As there was about 30% of the population all over the world living in the cities at 1950 this ratio now reached to more than 50% and probably will be at the rate of 80% by the end of 2050 (Bettencourt and West, 2010).

Natural flow regime is a concept for defining the dynamic hydrologic situation of a stream or flow in an undeveloped and unchanged type of ground. Some of the most important characteristics of this concept are: rate of change, predictability, duration, frequency and magnitude (Poff, 1997). Rapid urbanization severely alters the natural flow regime, by decreasing the infiltration rate and increasing the surface runoff and this leads to reduction of ground water recharge rate (Leopold, 1968).

Nigussie and Altunkaynak (2016) investigated the effects of urban growth in Ayamama watershed located in Istanbul, Turkey on hydrologic response of the watershed with considering the SLEUTH urban growth model under four land use scenarios. These scenarios are: 1- unrestricted growth of the watershed, 2- restricted growth of the watershed with aim of protective growth of ecologically sensitive areas, 3- watershed growth under the incorporation of Project Canal Istanbul (PCI) and 4- watershed growth under incorporation of (PCI) with envirnomental and ecological protection policies. As a result they found that in case of third scenario there will be highest peak discharge and the shortest time to peak.

Wang and Altunkaynak (2011) developed two rainfall-runoff models using SWMM and Fuzzy Logic approach for the Cascina Scala watershed located in Pavia Italy for camparing the model runoff results. According to their research fuzzy logic approach only outperforms in generally large rainfll events and in case modification of impervious ratio is not applied to improve the SWMM model resluts. Additionally SWMM model can provide a time varying hydrograph as model results while fuzzy logic model is unable to produce such a result because of limitation of the methodology.

Palla and Gnecco (2015) developed a model by using EPA SWMM based on implementing green roofs and permeable pavements as two kinds of LID controls by replacing different fractions of effective impervious area of a study area, located at the urban catchment of colle ometti, Genoa Italy. Mentioned catchment has 4.56 (ha) area in total with 60% impervious area which mainly consist of rooftops (31% of total) and roads and parking lots (28% of total). They investigated the reduction of peak flow, volume and delay of hydrographs by replacing 0%, 20%, 50% and 100% of roof tops by green roofs and 16% of parking lots by permeable pavements. For this purpose they used three different rain storms with the return periods of T=2, 5 and 10 years. They noticed that for an effective benefits they need a reduction of EIA more than 5% this is while for a simulated storm with 2-year return period and for the EIA reduction of 11% and 36% peak reduction will be range from 0.10 to 0.45, volume reduction will increase from 0.05 to 0.23 and finally hydrograph delay will be 0.03 to 0.19.

Qin et al. (2013) used an urbanizing catchment located at Guang-Ming district of china for studying the effects of three different types of LIDs including bio-swales, permeable pavement and green roofs. The effects assessed by analyzing the total flood volume reduction for several storm events with different characteristics and compared with the conventional drainage system. Also they investigated the flood volume reduction for storm events with different characteristics in amount, duration and peak value location. They calibrated their model with the data measured on a specific event and Root Mean Square Error (RMSE) method. The scenarios established on replacing impervious surfaces with swales, permeable pavements and green roofs with the total ratio of respectively 10%, 22% and 15% for each. On the other hand the storm events modeled for different return periods of 1, 2, 5, 10, 20, 50 and 100 years which were different in duration, total volume and time to peak ratio. They noticed that swales perform best when there is an early peak in the storm event, for a storm with relatively middle peak, permeable pavements do more effective job and finally green roofs seem to be more effective at the storms with a late peak ratio.

Wen et al. (2014) developed a model for quantifying the effectiveness of green infrastructure on urban communities in reduction of peak and volume of urban floods. They presented five scenarios like: green area expansion, converting to concave green area, construction of retention ponds, using permeable pavement and combination of these practices together. The district of Haidian in Beijing China selected for this simulation which has 54,783 m^2 area in total with 30% of green pervious area. Four storm events were selected for the simulation with return periods of: 1, 2, 5 and 10 years and 24-hours duration. The research revealed that one single green infrastructure has limited capacity for reducing the flood volume or peak flow, but integrated GI configuration is much more effective, such as reducing the total runoff from 100% to 85% and peak flow from 100% to 92.8% respectively for the storms events with the return periods of 1, 2, 5, and 10 years.

Zhang and Guo (2015) used a long term rainfall data of Atlanta and modeled the performance of permeable pavements and evaluated the average runoff reduction of permeable pavements by using EPA SWMM. Permeable pavements usually consisted of 3 layers which are surface layer, soil layer and stony storage or reservoir at the bottom. One under drain facility is optional and can be considered and added to system. As characteristics of input data they mentioned a 61 years rainfall record, with approximate annual precipitation of 1299.7 mm and highest intensity of 90.9 mm/h, additionally loam soil considered for native soil. They noticed that LID-SWMM model has a better performance in simulation with relatively short time steps. Also they proposed representing permeable pavement as a regular subcatchment instead of LID practice as an alternative method for modeling.

Gülbaz and Kazezyılmaz-Alhan (2013) investigated the effects of urbanization on Sazlıdere watershed modeled and calibrated by EPA SWMM. They believe that increasing population and the shifting which occurs from rural to urban areas by time, will result in unwanted changes in flow concentration time, flow rate and water quality. Sazlıdere watershed is located in Istanbul and by providing 55 million m^3 water annually plays an important role in drinking water supply. By installing appropriate gauges on the filed they could measure the rainfall and flow data and calibrate some principal properties of filed such as: Manning's roughness coefficient, Hydraulic conductivity and initial moisture condition of soil. They investigated the effects of population growth, extreme urbanization and extreme storm events on the watershed flooding and noticed that for the year 2035: there will be 10% increase in flooding amount in case of population growth, 64% and 126% increase in flooding amount due to the respectively 60% and 100% extreme urbanization scenario in 2035 and also for the extreme storm scenario there will be 69% and 48% increase in amount of flooding for two different events if the channels cross sections remain the same as current situation.

Kong et al. (2017) investigated the responses of different scenarios based on LID practices to evaluate the reduction of stormwater runoff at the city district level. They noticed that even different LIDs have positive effect in runoff reduction but it is not quite adequate and cannot be at the pre-development range. The average annual rainfall amount was 1108.3 mm and total study area was 838 ha. Pre-developed area was only consist of 5.8% impervious area and supposed to reach 39.63% after urbanization. A digital elevation model (DEM) of the area by resolution of 5m x 5m was used for the catchment delineation and boundary adjustments. Lad cover data was gained by using GIS data of the area. A 10-year return period storm event was used for the model development. Results showed that after urbanization and by using just traditional sewer systems, pervious areas will decrease 33.3% and this will lead to 92.9% and 90.9% increase in runoff and runoff coefficient respectively. Also there will be 31.7% increase in peak flow and it will occur 35 min earlier. After implementing LID practices including green roofs, porous pavements, vegetative swales and rain gardens in different ratios (10.3%, 5.4%, 1.0%, 2.2%) the runoff volume and runoff coefficient decreased respectively 16.69% and 15.87%. The results also showed that by designing the overland flow path and blocking the impervious areas connectivity with an optimized LID the flooding risk will be decrease more effectively.

Gülbaz et al. (2019) developed a flood model for Ayamama river watershed by using EPA SWMM and WMS programs and investigated the flood depth and volume and prepared a flood hazard map for the study area. They also validated their models accuracy based on a previous fatal flood event observations and reports. They used kinematic wave as routing method and horton for infiltration method. Flood depth and flood volume computed by the model for 5 different critical points inside the watershed. The values of results for these points are: flood depth (m): 13.75, 2.19, 1.58, 0.87, 0.85 and obtained flood volumes respectively are (m^3): 1651×10^3, 398×10^3, 209×10^3, 125×10^3 and 162×10^3. These valuse are in a good agreement with the observations at the study belonging to the previous fatal flood event. However, they did not consider storm water collection system in model setup. It is assumed that all the water is collected by surface runoff, which may affect the model accuracy.

2. DATA

One of the most important and time consuming parts of this thesis project is the data collection and preparation. We tried to use the highest quality topographical data for elevation assessments and catchment delineation purposes and also an especially effort consumed for land cover, land use defining purposes based on the aerial photography and Auto CAD file of the study area. It is necessary to mention that the accuracy of this model and its results is highly related to the spatial, topographical and meteorological data.

2.1 Spatial Data

The study area is located in ITU main campus Maslak, Sarıyer district at North-West of the Istanbul province, Turkey. For GIS projection, UTM WGS84, Zone 35 (24° E - 30° E – Northern Hemisphere) has been used. Because of lack of valuable infrastructure data for the eastern part of the campus only western part of the campus modelled and investigated in this study. The total area of study area is equal to 1.08 km^2 and consisted of mainly faculty buildings, roads and green areas.

Figure 2.1: Istanbul Technical University main campus location.

2.1.1 Land cover data :

The locations and physical features (i.e. Perimeter, Area, etc.) of the buildings and facilities achieved by using the Auto CAD file, given by ITU construction affairs office located at main campus of the university.

This Auto CAD file contains essential information about the locations of the sewer and drainage system junctions and pipelines like the locations of the manholes, length, diameter and slope of the pipes for both sewer system and drainage system and etc. Also, this Auto CAD file was used for obtaining the characteristics of various surface types like buildings, parking lots, roads and green areas in the campus along with the aerial photo of the campus provided by GIS programs.

Figure 2.2 shows the Auto CAD file of the campus which used for several purposes and also as a sublayer in GIS programs.

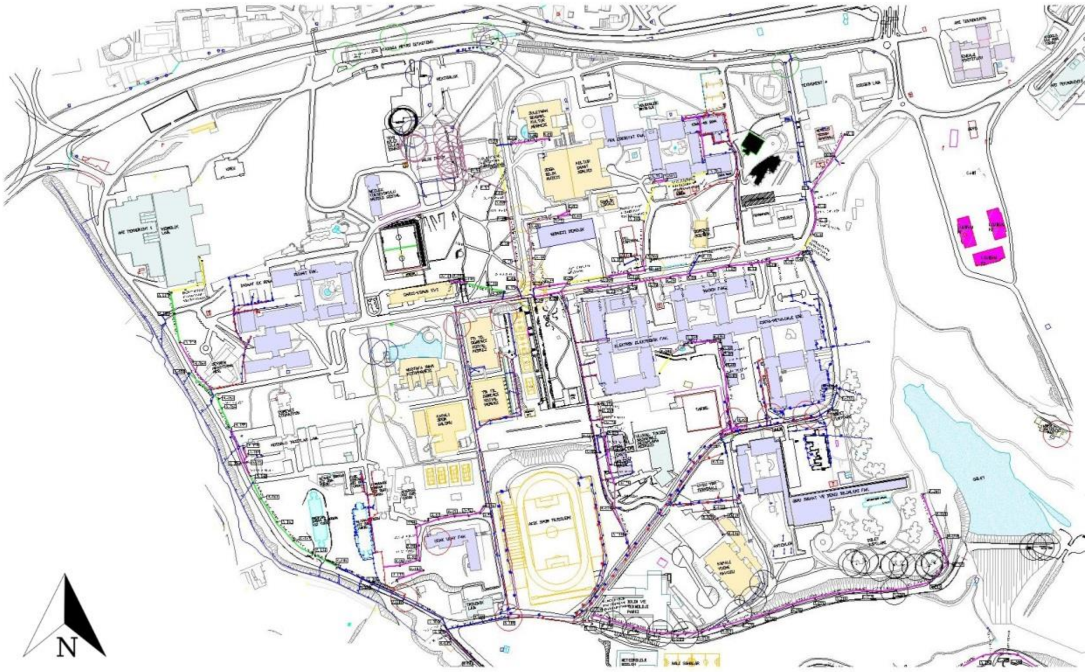


Figure 2.2: Detailed Auto CAD map of ITU main campus buildings and facilities.

Buildings and faculties identified with purple, blue and yellow colors, roads and parking lots presented with black binary lines and ITU gölet illustrated with bright blue color on the map.

Also the aerial photo of the university campus used for defining the wooded areas, grass areas and some previously undefined green areas. For this purpose, Arc GIS 10.4 program has been used.

After dividing the study area into the several land cover surface types, essential information of them such as: total area, percent of occupation, impervious or perviousness were obtained using the Arc GIS 10.4 program and Microsoft Excell 2010.

Figure 2.3 shows the land cover map of the study area. As presented in the figure and mentioned before, an especially effort and time consumed to provide an accurate, detailed and high resolution land cover map for the study area.

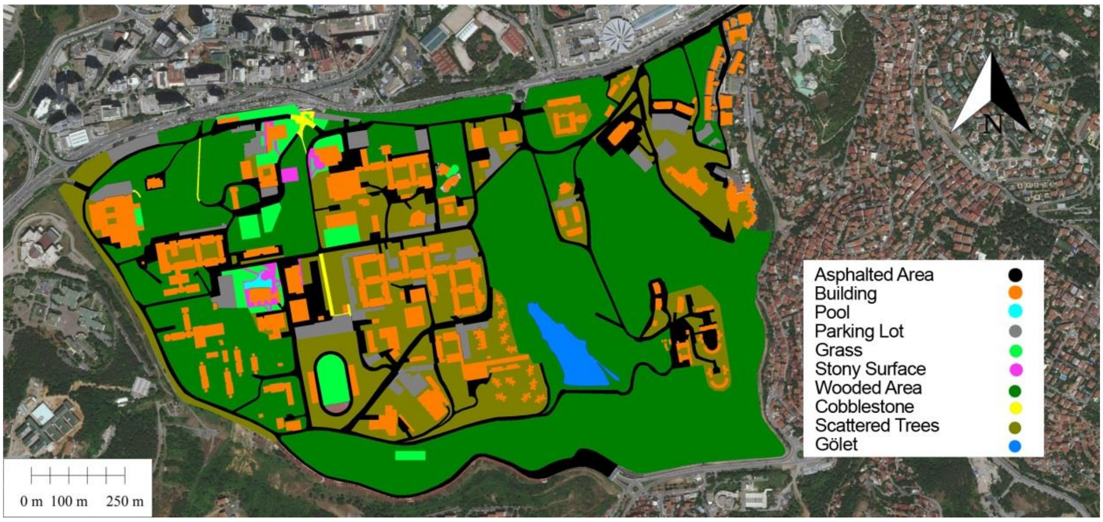


Figure 2.3: Land cover map of ITU main campus.

The information obtained from this map will be a baseline data for our calculations for each sub catchment characteristics.

2.1.2 Infrastructure data:

The locations of pipes and junctions, diameter and slope of pipes for the current drainage and sewer systems existed in the study area also achieved from the Auto CAD file given by ITU construction affairs. These information transferred to the GIS program as a distinctive sub layer and then turned into the points and lines for specification of the manholes and pipes.

Other information related with the elevation of infrastructure system elements obtained from topographical data of the study area by GIS software.

Figure 2.4 shows the map of current drainage system of the study area including the pipelines, inlet points, connection points and outfall points. A detailed sample section of the infrastructure facilities presented at Figure 2.5 obtained from the Auto CAD file of the university campus.

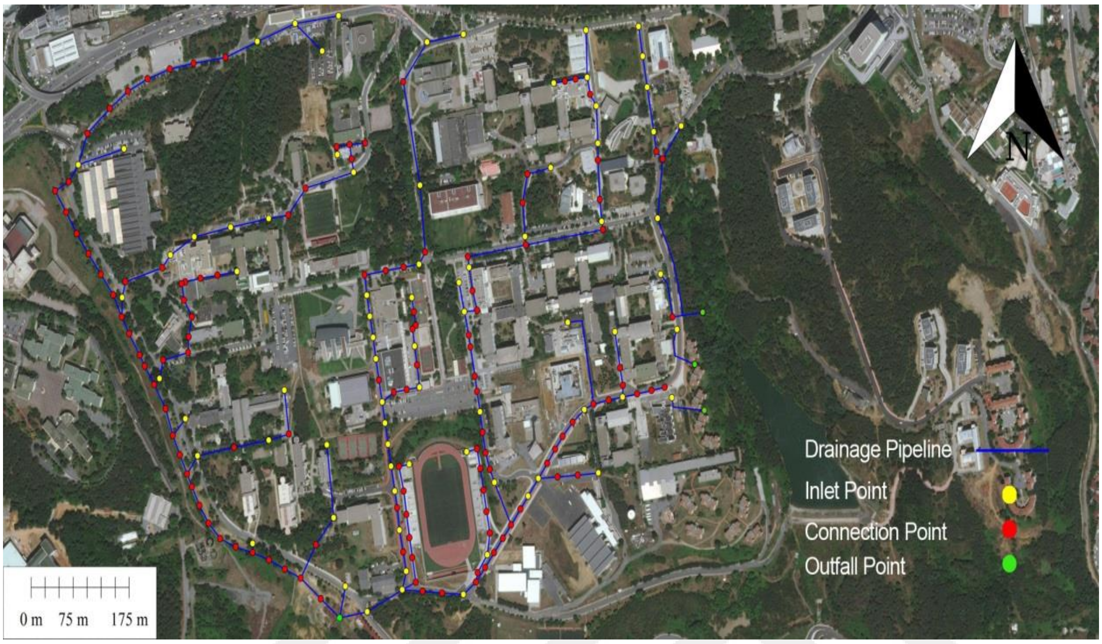


Figure 2.4: Detailed map of the drainage system of the ITU main campus.

Figure 2.5 shows an example of existed drainage system and sewer system section in the university campus which inputted as infrastructure data to the model.

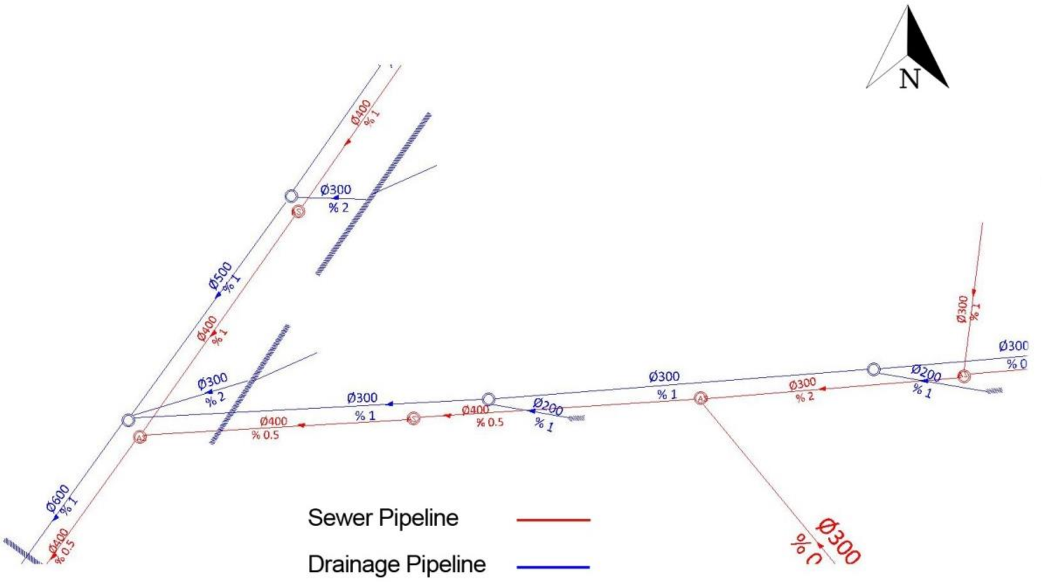


Figure 2.5: Example of drainage and sewer system detail.

The infrastructure system of the study area consisted of two binary pipelines one for sewer system and one for drainage system. As presented in Figure 2.6 both the sewer and drainage system of the study area consisted from PVC pipes with circular cross sections.

Further field investigations has done for validating the accuracy of infrastructure data, and also locating some missing junctions.A precious picture collection of the manholes, inlet and outlet points and pipes which used in the drainage system created after the field investigations and survey finished.

Figure 2.6 shows the installation of sewer and drainage pipes, beside each other as there is at the infrastructure data in CAD format. The photo was taken while renewal construction works was in run at ITU main campus.

Figure 2.6: Drainage & Sewer pipe lines, ITU Main Campus.

Also Figure 2.7 shows a sample of inlet points at the university campus which is used for rain water entry to the drainage system.

These points illustrated with yellow dots at Figure 2.4 Detailed map of the drainage system of the ITU main campus.

Figure 2.7: One sample of rain water inlet point at ITU main campus.

Additional to the inlet points there are manholes implemented in the infrastructure system for connecting the pipes together. The third type of infrastructure points are outfall points which are the end points of flow conduction in the system.

Figure 2.8: Main outfall point of the ITU main campus drainage system.

Figure 2.8 shows the main outfall point of ITU campus drainage system. Campus drained waters first conducted by the drainage system to this point and after moves to be released to the sea by ISKI made canalization. Figure 2.4 presents a good visual map of inlet, connection and outfall points at the study area.

After specifying the locations and elevations of these points they will input to the SWMM model as Nodes. Further information about nodes and their input parameters will be presented at the model preparation section of this report.

2.2 Topographic Data:

In this model a DEM file of the Study area with the resolution of 5m ($\Delta X = \Delta Y = 5m$) has used for flow direction and flow pathway finding computations. By using such a high resolution topographic data it is tried to reach more accurate results in this research work. Also, the mentioned DEM file used for sub catchment delineation, junctions elevation assessment and sub catchments slope calculations. All of these computations done by using Arc GIS 10.4 program.

Figure 2.9 shows the DEM file of the study area overlaid the land cover layer of the study area. This approach will lead to obtaining the elevation of the different points and also defining the subcatchments border due to the DEM and inlet point availability for each prospective sub catchment.

Figure 2.9: Overlaid layers of DEM and land cover for the ITU main campus.

As presented in Figure 2.9 after overlaying the DEM and land cover map of the study area it will be possible to evaluate the elevation of any purposed point on the map. This approach beside catchment delineation for the study area using DEM file will lead to sub catchment border delineation for SWMM model. For this purpose firstly catchment delineation for the study area done by using DEM and computing the flow pathway in Arc GIS.

As depicted in Figure 2.10, ITU main campus composed of 5 catchments numbered 1 through 5. Surface water in catchment 1 and 2 after draining into the drainage system, directly conducted to our systems main outfall point. Surface water of catchment 3 and 4 also after draining into the system and after reaching the catchments end point will conduct by the conduits to the drainage system’s main outfall point, joining the drained waters of catchments 1 and 2. And about catchment 5, its surface water collects at the ITU Gölet.

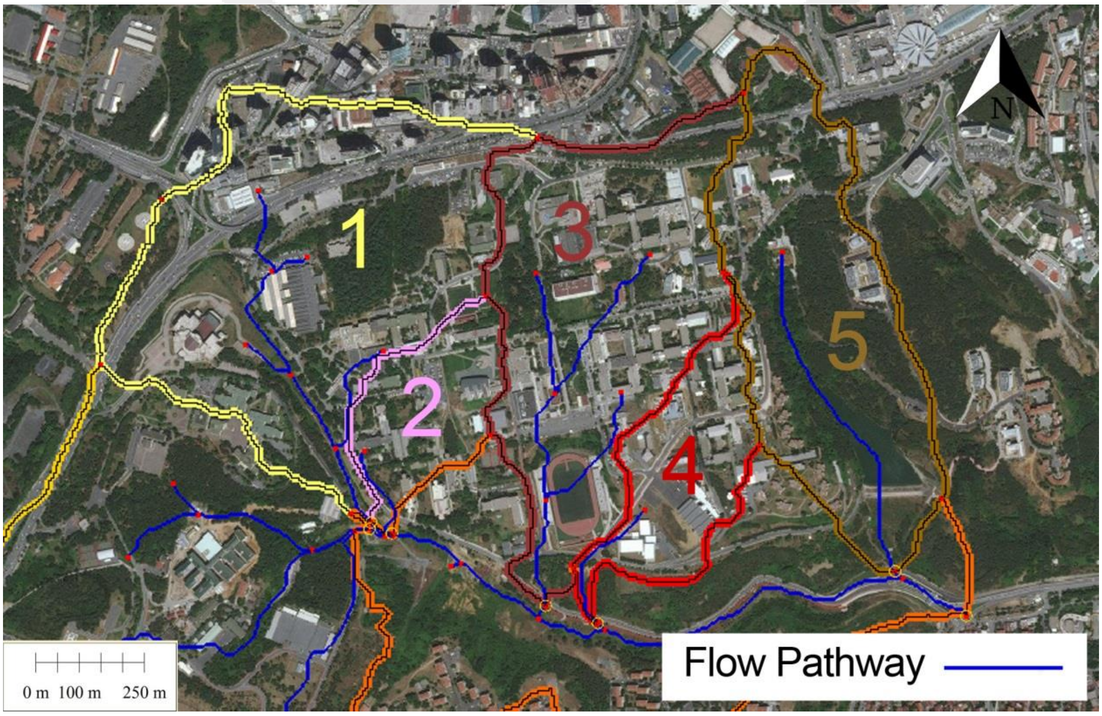


Figure 2.10: Catchments boundary delineation of ITU main campus.

Drained water and surface runoff after reaching the systems outfall point and joining the other catchments’ drained water, (which are out of the university territory and not defined with numbers on the map figure 2.10) , will be conduct by the ISKI made canalization and be released to the Marmara sea at the Bosporus.

As it is mentioned before, ITU main campus sub catchment's borders also delineated by using the DEM file of the study area, location of the campus drainage system inlet points and also due to the catchment's scheme of the campus.

ITU main campus as presented in Figure 2.11 consist of 77 sub catchments in total and this subcatchments will be modeled in SWMM for simulating the rainfall-runoff model of the study area.

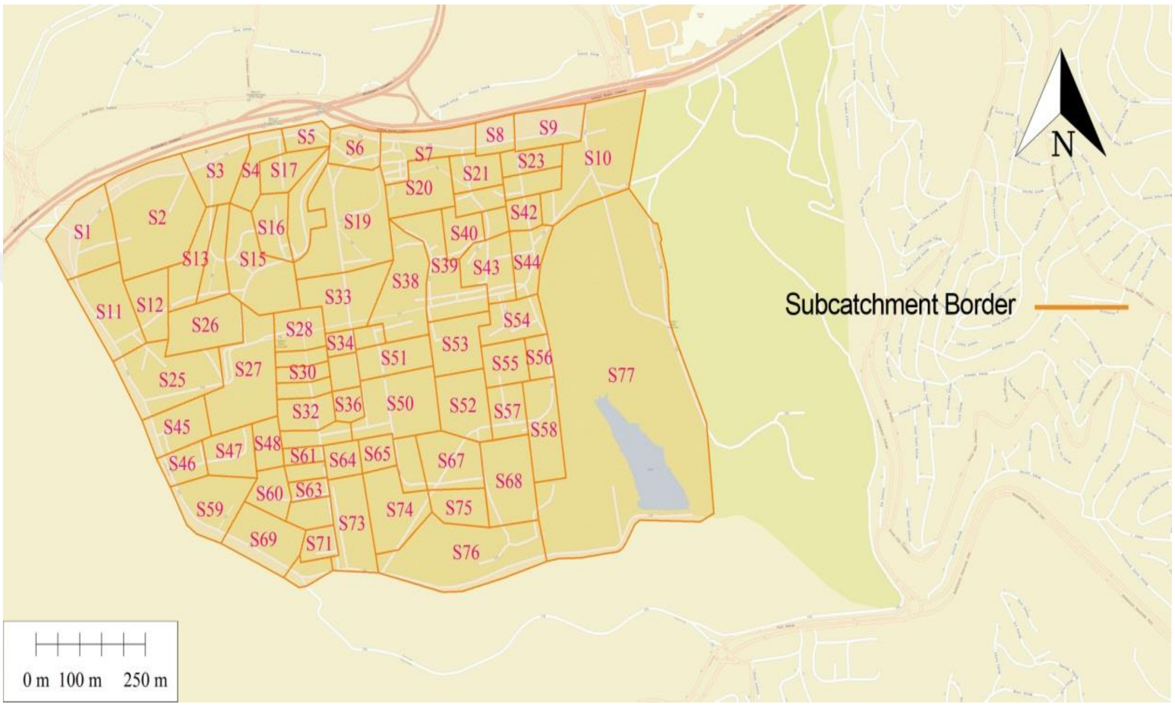


Figure 2.11: Map of the ITU main campus divided into 77 sub catchments.

2.3 Soil Properties:

For developing this rainfall-runoff model there is a need for characterizing the soil properties of the study area. These data will be use in infiltration calculations of the model by EPA SWMM program. In this model initial values for soil suction head (Su), hydraulic conductivity (K) and other characteristics of the soil obtained from previous studies. (Gülbaz & Kazezyılmaz-Alhan 2013). And then calibrated due to the field measurements and simulated results. Detailed information about model calibration and validation presented at the results and discussion chapter of this report.

Table 2.1 shows some of the values used for soil properties in this model.

Table 2.1: Soil characteristics of study area.

	Before calibration	After calibration
Soil Type	Silty Clay Loam	Sandy Clay
Hydraulic Conductivity (K) (mm/h)	1.01	0.5
Suction Head (Su) (mm)	270	240
Porosity (fraction)	0.471	0.43

2.4 Meteorological Data :

Meteorological data for this model provided by Sariyer Meteorology Station located near the study area at Sariyer district of Istanbul.

Figure 2.12: Location of Sariyer Meteorology Station and ITU main campus.

This rainfall data include: precipitation predictions for the 5 storm events with return periods of 2, 5, 10, 25, and 50 years and with duration of 2 hours and a long term hourly rainfall record from November 2017 to November 2018. Additionally, for the same period and from the same station, the daily minimum and maximum temperature data obtained and used for evaporation calculations which done by

SWMM. The rainfall data for the above mentioned storm events inputted to the model according to the normal distribution function and with 10 minutes intervals.

These storm events will use for evaluating the effects of LIDs on peak runoff and runoff volume reduction and the long term rainfall data will use for obtaining the approximate annually discharge volume from the drainage system of the study area.

3. METHODOLOGY

3.1 Introduction:

EPA SWMM firstly developed in 1971 by U.S Environmental Protection Agency, and since then upgraded several times and increased in popularity day by day. EPA SWMM is a physically based, discrete-time, dynamic rainfall-runoff modeling program for simulating the runoff quality and quantity occurring in a single event or long term events in urban or rural areas. It employs the principles of conservation of mass, energy and momentum (Rossman 2015).

This program relies highly on the spatial information of the study area. SWMM tracks the runoff quality and quantity after calculating the evaporation and infiltration to the subsoil in each sub catchment, based on water mass balance equation.

SWMM uses a couple of environmental segments for modeling the projects. They are respectively as follows:

- The Atmosphere segment: Responsible for precipitation.
- The Land Surface segment: Consist of sub catchments which receive the precipitation and convert it to the groundwater via infiltration or surface runoff, depended to the type and condition of the land cover.
- Groundwater segment: Receives the water via infiltration and modeled as aquifer in SWMM.
- Transport segment: Consist of a network of conveyance elements like pipes and open channels which receives water via nodes and junctions.

3.1.1 Some of visual objects in SWMM

- Rain Gage: Provides precipitation data for subcatchments by using time series rainfall data or single event rain fall data.

- Sub catchment: Represents a part of surface which rainfall in all of that part drains to a specific point and has a predetermined ratio of pervious and impervious portion.
- Junction Node: A place for external surface waters to inflow or connecting the conduits to each other, generally known as manholes.
- Outfall Nodes: Terminal nodes for a drainage system where dynamic wave routing for a flow ends there.
- Conduits: Pipes or open channels which conduct water between two specific nodes.

3.1.2 Modeling capabilities

- Time dependent rainfall modeling
- Surface water evaporation
- Snow mass collection and melting
- Infiltration modeling
- LID modeling
- Water interception in surface depression storages
- Nonlinear reservoir routing
- Dynamic wave, kinematic wave and steady flow routing.

3.2 Basic Equations And Definitions:

3.2.1 Surface runoff:

This chapter presents the methods which SWMM employs for converting the precipitation to surface runoff. SWMM is a model which permits the user to divide the study area to a various quantity of sub catchments with different shapes and features. Then the program uses a nonlinear reservoir model to calculate the surface runoff due to the precipitation and correspond to each sub catchment.

From conservation of mass in each sub catchment SWMM calculates the change in depth per unit of time with the formula below:

$$\frac{\partial d}{\partial t} = i - e - f - q \tag{3.1}$$

i: Rainfall or snowmelt rate (mm/s)

e: Evaporation rate (mm/s)

f: Infiltration to the subsoil rate (mm/s)

q: Runoff rate (mm/s)

All the parameters are per unit area.

Assuming that each subcatchment has a width of “W” and slope of “S” and a height of “d” SWMM uses Manning equation for obtaining volumetric flow rate for each sub catchment:

$$Q = \frac{1}{n} S^{1/2} A_x R_x^{2/3} \tag{3.2}$$

Q: Volumetric flow rate ($\frac{m^3}{s}$)

n: Surface roughness coefficient

S: Average slope of sub catchment

A_x: Area across the sub catchment’s width (m^2)

R_x: Hydraulic radius associated with the area (m)

3.2.2 Flow routing:

SWMM uses conservation of mass and momentum equations for flow routing, generally known as “Saint Venant Equations”.

Three options exist for flow routing in SWMM:

- Steady Flow Routing
- Kinematic Wave Routing
- Dynamic Wave Routing

Steady Flow Routing:

It is the simplest type of flow routing in SWMM. It assumes the flow in each time step is ununiform but steady. So it just transfers the inflow hydrographs to the downstream end of the pipes with no delay and reshape. This type of routing method cannot be operational for pressurized flows, backwater effects, entrance or exit losses and etc. computations. It is just suitable for preliminary analysis by using long term continuous simulations.

SWMM uses continuity equation and a simplified form of momentum equation for flow routing in conduits in steady flow routing status.

- Continuity equation:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \tag{3.3}$$

- Momentum equation in steady flow routing:

$$\frac{\partial Q}{\partial t} = \mathrm{g}\ \mathrm{A}\,\frac{\partial H}{\partial x} \tag{3.4}$$

Kinematic Wave Routing:

In this routing method system applies the continuity equation and a simplified type of momentum equation in each conduit. This routing method allows the flow to be changed both spatially and temporally inside the conduit and this results in attenuated and delayed outflow hydrographs after conveyance of water through drainage pipes. This type of routing method cannot be operational for pressurized flows, backwater effects, entrance or exit losses and etc. computations but it can remain stable in modeling with moderately long time steps.

- Momentum equation in kinematic wave routing:

$$\frac{\partial Q}{\partial t} = \mathrm{g}\ \mathrm{A}\,\frac{\partial H}{\partial x} + \mathrm{g}\ \mathrm{A}\ \mathrm{S}_f \tag{3.5}$$

Dynamic Wave Routing:

This routing method applies the complete one-dimensional Saint Venant flow equations which consist of continuity and momentum equations in conduits and volume continuity equations at nodes and therefore provides the most real and accurate results relatively to others. In this method it is possible to model the pressurized flow and calculate the backwater effect in conduits and nodes.

- Momentum equation:

$$\frac{\partial Q}{\partial t} = g\,A\,\frac{\partial H}{\partial x} + g\,A\,S_f + \frac{\partial(\frac{Q^2}{A})}{\partial x} \tag{3.5}$$

- Continuity equation at a node:

$$H_{t+} = H_t + \frac{\Sigma Q_t^{\Delta t}}{A_{st}} \tag{3.6}$$

In pipes with fully pressurized flow and with circular force main cross-section SWMM instead of Manning equation uses Hazen-Williams or Darcy-Weisbach formulas.

- Hazen-Williams formula (SI) :

$$h_f = 10.7 \times (\frac{Q}{C})^{1.852} \times \frac{L}{D^{4.87}} \tag{3.7}$$

Where:

h_f: Friction head loss (m)

Q: Discharge rate of the pipe (m^3/s)

C: Hazen-Williams coefficient

L: Pipe length (m)

D: Pipe diameter (m)

Hazen-Williams coefficient C, supplied as one of the cross section parameters and changes inversely with surface roughness.

- Darcy-Weisbach formula (SI) :

$$h_f = \frac{fLV^2}{2gD} \tag{3.8}$$

Where:

h_f: Head loss (m)

f: Darcy-Weisbach friction factor

L: Pipe length (m)

D: Pipe diameter (m)

V: fluid velocity ($m/_s$)

g: Gravity acceleration ($^{m}/_{s^2}$)

The choice of selecting which method to use is depended on the user decision. In this simulation Hazen-Williams method used for force main equation in flow routing computations.

It is also useful to mention that SWMM model is stable numerically when the following inequality met in the model:

$$\Delta_t \leq \frac{L}{\sqrt{gD}} \tag{3.9}$$

Where:

Δ_t: Each computational time step (S)

L: Length of pipe (m)

g: Gravity acceleration ($^{m}/_{s^2}$)

D: Maximum pipe depth (m)

3.2.3 Infiltration:

There are five options for calculating the infiltration to the sub soil layer in SWMM:

- Horton's Method:

Horton's method based on empirical observations. This method is applicable only when rainfall intensity exceeds the infiltration capacity of the soil. In this method infiltration decreases exponentially from an initial maximum rate to a minimum rate at a long term rainfall event. Horton equation is given below:

$$F(t_p) = \int_0^{tp} fp\, dt = f_{min} .t_p + \frac{(fmax - fmin)}{k} .(1 - e^{-k.tp}) \tag{3.10}$$

Where:

$F(t_p)$: Cumulative infiltration volume at time (t)

t_p: The equivalent time for the actual infiltrated volume (hr)

f_p: The infiltration rate at time, t_p

f_{min}: Minimum or constant infiltration rate at t=∞ (in/hr)

f_{max}: Maximum or initial infiltration rate at t=0 (in/hr) k: Decay constant (1/hr)

- Modified Horton Method:

This is a modified version of the previous Horton method and uses cumulative infiltration in excess of minimum rate as its state variables, instead of time along the Horton curve.in this case the results of infiltration in low intensity rainfalls are more accurate.

- Green-Ampt Method:

This method supposes a sharp wetting front in the soil, separating the saturated soil above and some initial moisture content below. In this method the recovery rate of moisture deficit of soil during days with no rainfall is empirically related to the soil hydraulic conductivity. The integrated form of Green-Ampt equation is given below:

$$F = K_s + \psi_s \, \theta_d \ln \left(1 + \frac{F}{\psi s \; \theta d}\right) \tag{3.11}$$

Where:

F: Cumulative infiltration (mm)

K_s: Saturated hydraulic conductivity (mm/hr)

ψ_s: Capillary suction head along the wetting front (mm)

θ_d: Initial moisture deficit

- Modified Green-Ampt Method:

This method is modified version of the previous Green-Ampt Method. Its function based on not depleting the moisture deficit of the top surface soil during initial times of low rainfall as was done in the previous method. This procedure causes more accurate results especially when storms accrue with long initial periods with intensities below the soil’s saturated hydraulic conductivity. In this thesis, Modified Green-Ampt Method used for infiltration calculations.

- Curve-Number Method:

This method first developed in 1954 and developed based on NRCS (SCS) Curve Number Method for estimating runoff. This method suggests that total infiltration capacity of a soil can be reached from the soils tabulated curve number. In a rainfall event this capacity decreases as a function of cumulative rainfall and the capacity remained.

Classic form of CN method used for runoff calculations is given below:

$$Q = \frac{P^2}{P + S_{max}} \tag{3.12}$$

Where:

Q: Total event runoff (mm)

P: Total event precipitation (mm)

S_{max}: Soil's maximum moisture storage (mm)

S_{max} is derived from a tabulated CN that depends both on soil type and prior conditions:

$$S_{max} = \frac{1000}{CN} - 10 \tag{3.13}$$

Assuming these equations, it could conclude that the amount of water which does not turn to runoff, infiltrates to the sub soil so the total infiltration loss can be obtain by :

$$P - Q = F \tag{3.14}$$

$$F = P - \frac{P^2}{P + S_{max}} \tag{3.15}$$

Where:

Q: Total event runoff (mm)

P: Total event precipitation (mm)

F: Infiltration loss (mm)

3.3 LID Controls

LID controls are a combination of multiple vertical layers consisted of Pavement, Surface, Soil, Storage and Drain. Each layer has its own properties and with other layers makes a LID control concept. These LID controls can be modeled as layers with properties in area basis so can apply to the different surfaces with different scales in sub catchments. SWMM by using a moisture balance can track the amount of moisture moving and storing between layers and within each LID control. The main function of these LID controls is increasing the infiltration and evaporation from the sub catchments and by this mean reducing the amount of runoff from sub catchment surface. Some of the LID controls existed in SWMM for modeling are listed below:

- Bio-Retention Cells: presented in SWMM as depression storages with an engineered soil mixture and a storage layer and a vegetation cover atop. Providing infiltration and evaporation for rain water.
- Rain Gardens: presented in SWMM as a type of Bio-Retention Cell which contains just engineered soil layer and a vegetation layer without storage unit beneath. Providing infiltration and evaporation for rain water.
- Green Roofs: presented in SWMM as another type of Bio-Retention Cell which contains a soil layer and a special drainage mat. Providing infiltration and evaporation for rain water.
- Infiltration Trenches: presented in SWMM as a narrow ditches usually alongside roads and sidewalks filled with coarse aggregates. Providing storage volume and time for infiltration of the rain water.
- Permeable Pavements: presented in SWMM as systems excavated and filled with coarse aggregate generally with gravel and a cover of porous pavement atop. Also it is possible to design extra drainage facilities like pipes under the gravel layer for improving the function of infiltration. Providing infiltration and storage facility for rain water.
- Vegetative Swales: presented in SWMM as channels and depression areas which the sides are covered with grass or vegetations. They reduce the speed of water passing through and allow them to infiltrate better.

The LID controls which considered to simulate in this thesis project and detailed information about their implementation will present in the model preparation chapter.

4. MODEL PREPARATION

In this chapter detailed information about different sections of model preparation process and input data will discuss.

4.1 Sub Catchments

First stage of this modeling approach is sub catchment delineation. Sub catchment delineation was done with the help of the DEM file of study area, the location of junctions and drainage inlets and land cover of the area. Prior information about sub catchment delineation process was given in data preparation chapter of this report.

After defining the sub catchments boundary in Arc GIS it is required to transport these information to SWMM. This model consists of 77 sub catchments with the total area of 1.08 km^2. The ratio of total impervious areas to the pervious areas is equal to 38.56%.

After completing the sub catchments drawing in SWMM program, sub catchment parameters should be specified. These parameters and input data include corresponding rain gage for the sub catchment, corresponding outlet point or sub catchment, sub catchment area, width, % slope, % impervious area to the pervious area of subcathment, Manning’s N for impervious and pervious percent of the subcatchment, depression storage for impervious and pervious percent of the subcatchment, % zero imperviousness, infiltration method and inputs of it, LID controls in case of existence and etc.

Most of these parameters specified based on the spatial data of each sub catchment and in this model Arc GIS 10.4 program used for this purpose. For the parameters related to the surface type, like Manning’s roughness coefficient and depression storages, SWMM manual used and parameters obtained (Rossman 2015).

Figure 4.1 shows the visual map of sub catchments modeled in SWMM.

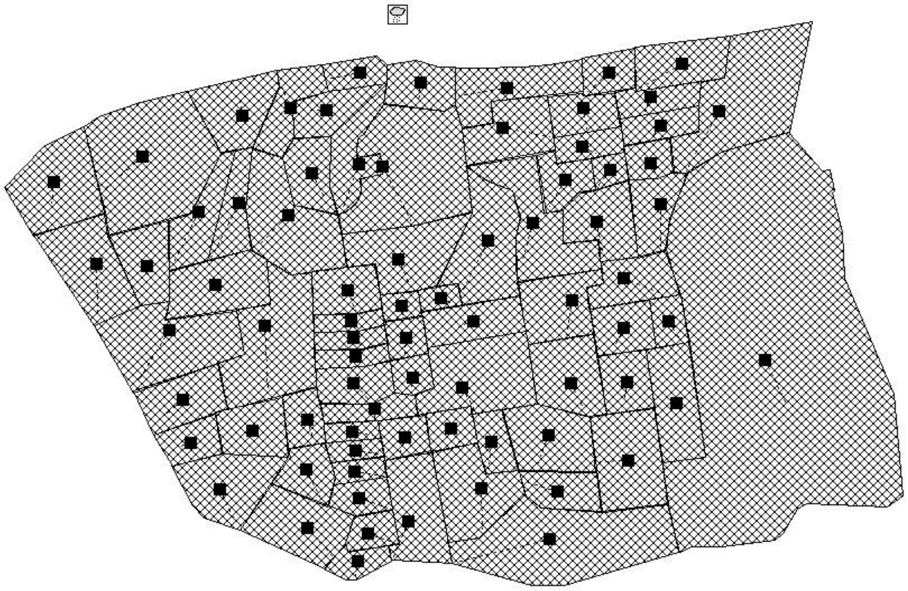


Figure 4.1: Sub catchment delineation of the study area in SWMM.

4.2 Nodes:

Two types of nodes represented in this model:

- Junction points
- Outfall points

Junctions are the nodes which connect the pipes to each other, usually we see them as manholes with a metal rim on the ground, or are an entry point for the rain water and seem as hatched trapdoors on the ground. (Figure 2.7). in total this model has 196 junctions. Detailed visual map illustrating the location and types of these nodes in the study area presented in the data chapter of this report (figure 2.4).

Outfall points are nodes which system's drained water exits the system form there and after this point there is no routing or calculations done on the water quantity or quality. The main outfall point of the drainage system located at the south of the study area (figure2.8).

Figure 4.2 shows the nodes of the drainage system in SWMM model. The nodes which illustrated with filled circles are connection or inlet points and the nodes illustrated with filled triangles are drainage system outfall points also line segments represent the pipeline of the drainage system.

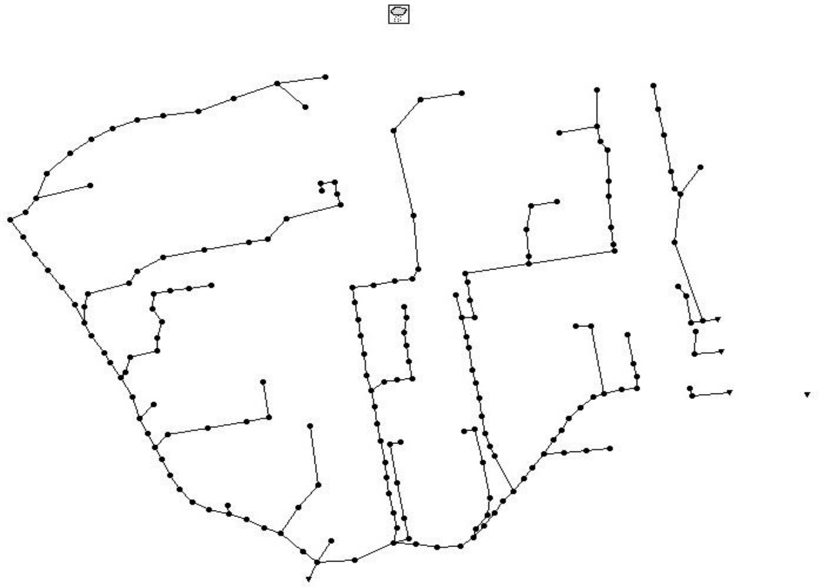


Figure 4.2: Visual map of conduits, junction nodes and outfall nodes which modeled at SWMM.

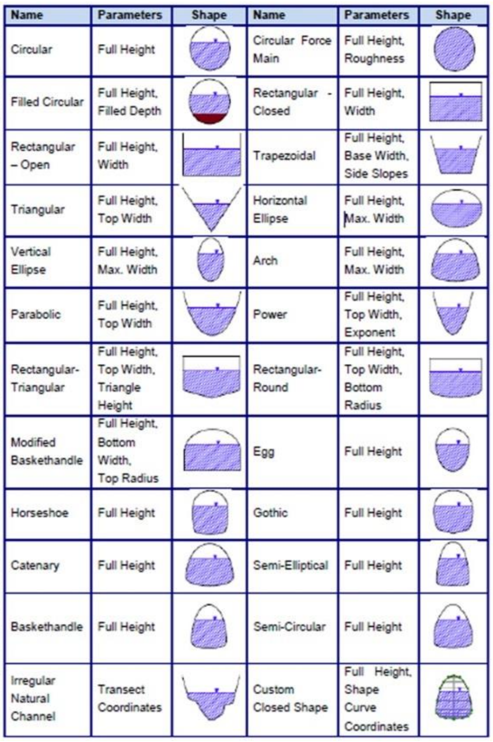
This model has 4 outfalls in total and except system main outfall, OUT1, other outfalls release corresponding captured rain water to the ITU Gölet.

Like sub catchments it is essential to specify the location of the junctions and their input parameters. Some of these input parameters of nodes are: treatment availability, invert elevation, Maximum depth, initial depth, ponded area and etc. Most of these information achieved by using the Auto CAD file of the University and the other information gained by Arc GIS program.

4.3 Conduits:

Conduits in SWMM are system elements which connect the nodes together and conduct drained water through. These links can be various in shape and material for example can considered as open channels or pipes, depended on the study area infrastructure. SWMM also can support irregular and natural cross sections for conduits. Figure 4.3 shows some common cross sections and their parameters which SWMM can model and also the pipe type implemented already in the study area for drainage network. The cross section shapes obtained from SWMM manual and pipe picture taken during site investigations. As it is obvious and as there is in real, circular cross section for the pipes selected in this model.

Some of the most important input parameters for the conduits are: Inlet and Outlet nodes, Shape, Maximum Depth, Length, Manning’s Roughness Coefficient, Inlet and Outlet Offsets and etc. Some of these information obtained from the CAD file of the University and other information like Manning’s Roughness Coefficient achieved by SWMM manual (Rossman 2015). In this model there are 197 conduits in total for the drainage system.



Name	Parameters	Shape	Name	Parameters	Shape
Circular	Full Height		Circular Force Main	Full Height, Roughness	
Filled Circular	Full Height, Filled Depth		Rectangular - Closed	Full Height, Width	
Rectangular – Open	Full Height, Width		Trapezoidal	Full Height, Base Width, Side Slopes	
Triangular	Full Height, Top Width		Horizontal Ellipse	Full Height, Max. Width	
Vertical Ellipse	Full Height, Max. Width		Arch	Full Height, Max. Width	
Parabolic	Full Height, Top Width		Power	Full Height, Top Width, Exponent	
Rectangular-Triangular	Full Height, Top Width, Triangle Height		Rectangular-Round	Full Height, Top Width, Bottom Radius	
Modified Baskethandle	Full Height, Bottom Width, Top Radius		Egg	Full Height	
Horseshoe	Full Height		Gothic	Full Height	
Catenary	Full Height		Semi-Elliptical	Full Height	
Baskethandle	Full Height		Semi-Circular	Full Height	
Irregular Natural Channel	Transect Coordinates		Custom Closed Shape	Full Height, Shape Curve Coordinates	

Figure 4.3: Sample cross sections in SWMM and sample pipe type of the ITU drainage system.

4.4 LID Controls:

LID controls are a combination of multiple vertical layers consisted of: Pavement, Surface, Soil, Storage and Drain. In most of the LID controls considering drain layer is optional and in this thesis project drain layer for purposed LID controls neglected. These layers can implement on surface by specifying the area and some other characteristics. Detailed information presented at methodology chapter of this report.

In this study three types of LID controls designed and implemented in combinations to several points of the ITU main campus with replacement usages of: 5%, 10%, 15% and 20% instead of impervious surfaces. These LID controls are:

- Green Roofs
- Permeable Pavements and
- Bio-Retention Cells

Sample figures for these LID controls prepared in 3D MAX program by considering the real structure of them with aim of better visualization. Figure 4.4 illustrates the typical combination of different layers in a Bio-Retention Cell.

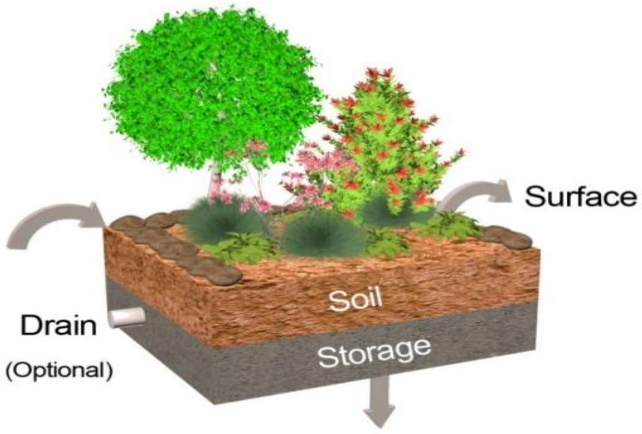


Figure 4.4: Sample figure of a Bio-Retention Cell modeled in SWMM

As presented in the figure with arrows after entering the surface runoff or direct precipitation to the Bio-Retention Cell some part of water losses through evaporation and infiltrating to the LID, and remaining part will overflow out of LID. Table 4.1 shows some of the most important parameters for the Bio-Retention Cells which considered in this model.

Table 4.1: Bio-Retention Cell characteristics.

	Surface	Soil	Storage
Berm Height (mm)	200	-	-
Vegetation Volume (Fraction)	0.2	-	-
Roughness (Manning's N)	0	-	-
Surface Slope (Percent)	1	-	-
Thickness (mm)	-	800	450
Porosity (Volume Fraction)	-	0.45	-
Field Capacity (Volume Fraction)	-	0.19	-
Wilting Point (Volume Fraction)	-	0.085	-
Conductivity (mm/Hr.)	-	10.92	-
Void Ratio	-	-	0.75
Seepage Rate (mm/Hr.)	-	-	0.508

Bio-Retention Cells in this model implemented in sub catchments: S11, S19, S27, S28, S31, S35 and S36. Corresponding to the Arı Teknokent 1 yard, Süleyman Demirel Cultural Center yard, near the Civil Engineering Faculty and surrounding area of the ITU main dining hall.

Decision making for the location of Bio-Retention Cells done due to the availability of the subcatchments area and also the sub catchments which were not appropriate for green roofs and permeable pavements.

Second type of LIDs which modeled in SWMM is Permeable Pavement, this LID control purposed to implement in some parking lots of the ITU main campus. The location and area of permeable pavements selected based on the availability and the impacts which will have on runoff reduction. Permeable pavements considered to implement in sub catchments: S1, S2, S6, S7, S16, S17, S18, S21, S27, S37, S38, S39, S49, S50, S51, S54, S66, S67, S75, S76 and S77. Corresponding to parking lots located at front of campus swimming pool, back of campus stadium, near electric engineering faculty, near rectorate building and two places near information center of ITU and etc.

Figure 4.5 illustrates the typical layer combination belonging to the permeable pavement which purposed to implement in study area and modeled in SWMM.

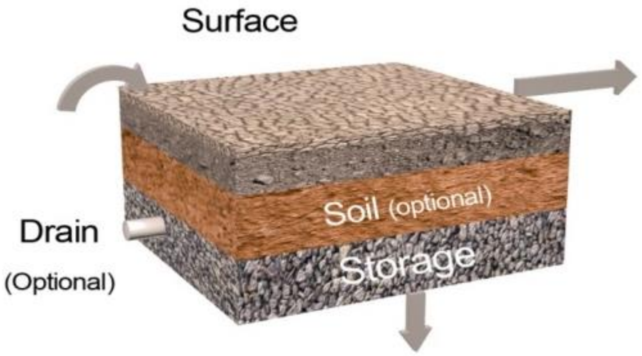


Figure 4.5: Sample figure of a Permeable Pavement modeled in SWMM.

For permeable pavement a layer of cobblestone for surface pavement and three other layers considered. At the bottom a layer of gravel will provide a good facilitate for storing the infiltrated water. Also it is optional to design a drain pipe at the storage layer for conducting excess water. Details and characteristics of modelled permeable pavements presented in Table 4.2 below.

Table 4.2: Permeable Pavement characteristics.

	Surface	Pavement	Soil	Storage
Roughness (Manning's N)	0.04	-	-	-
Surface Slope (Percent)	2	-	-	-
Thickness (mm)	-	100	450	450
Void Ratio	-	0.15	-	0.75
Permeability	-	120.39	-	-
Porosity (Volume Fraction)	-	-	0.45	-
Field Capacity (Volume Fraction)	-	-	0.19	-
Wilting Point (Volume Fraction)	-	-	0.085	-
Conductivity (mm/Hr.)	-	-	10.92	-
Seepage Rate (mm/Hr.)	-	-	-	0.508

Third type of LID controls purposed to model in SWMM and implement in study area is Green Roofs. The location and the area of Green Roofs decided due to the availability at the roof tops of buildings and the critical level of subcatchment inundation in case of storm event. The purposed places for implementing Green Roofs are located in sub catchments: S5, S12, S17, S20, S25, S26, S39, S40, S45, S53, S55, S56, S57, S58, S68 and S77 corresponding to the roof tops of buildings: rectorate building, civil engineering faculty, lojmanlar buildings some parts of mining engineering faculty and etc. Figure 4.6 illustrates a typical layer combination of a Green Roof.

Figure 4.6: Sample figure of a Green Roof modeled in SWMM.

As presented in Figure 4.6 a Green Roof consists of three layers of surface which are vegetations, soil layer and a drainage mat layer.

The characteristics of modelled Green Roofs presented in Table 4.3.

Table 4.3: Green Roof characteristics.

	Surface	Soil	Drainage Mat
Vegetation Volume (Fraction)	0.2	-	-
Roughness (Manning's N)	0.4	-	0.1
Surface Slope (Percent)	1	-	-
Thickness (mm)	-	150	25.4
Porosity (Volume Fraction)	-	0.45	-
Field Capacity (Volume Fraction)	-	0.19	-
Wilting Point (Volume Fraction)	-	0.085	-
Conductivity (mm/Hr.)	-	10.92	-
Void Fraction	-	-	0.5

Four general maps illustrating the locations of different LID types for the LID replacement percentages of 5%, 10% 15% and 20%, presented in the figures below. These LID replacement percentages simulated in SWMM model of the study area for analyzing the effects of these LID combination percentages on runoff peak flow and runoff volume reduction under five different rain storm events.

It is useful to mention that these colored schemes of the study area about LIDs, are just for identifying the locations of LIDs in 5%, 10%, 15% and 20% replacement scenarios and do not mean the occupied area for previously mentioned LID types. Figure 4.7 shows the locations and types of the LID components which are considered to implement the scenario of 5% LID replacement.

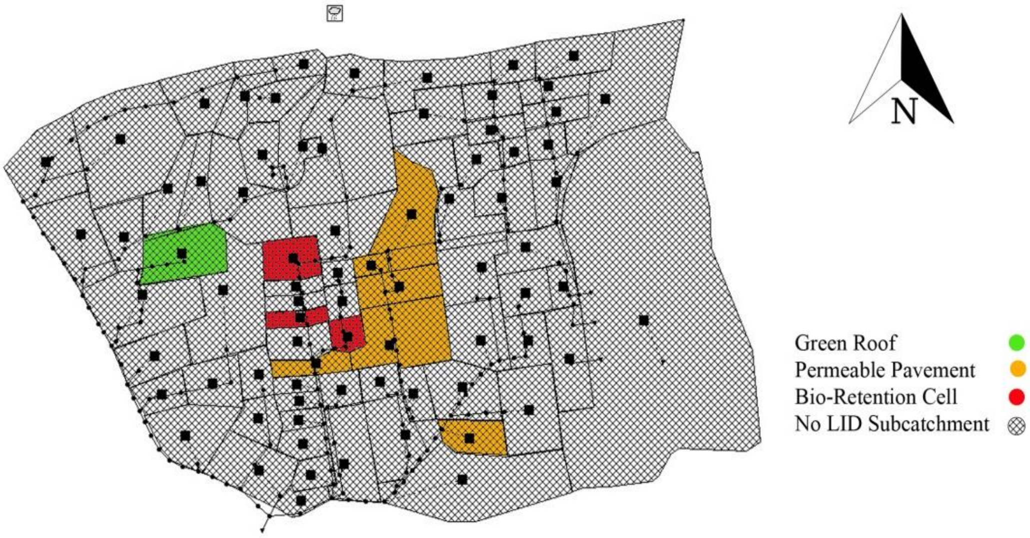


Figure 4.7: Visual map of different LID types and locations in 5% LID replacement scenario.

Figure 4.8 shows the locations and types of the LID components which are considered to implement the scenario of 10% LID replacement.

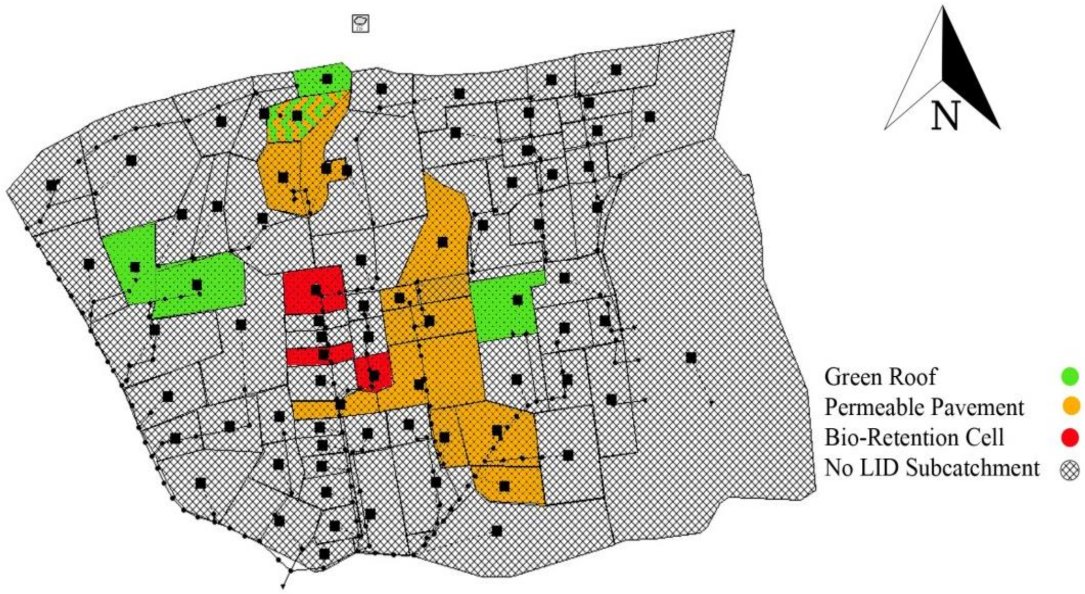


Figure 4.8: Visual map of different LID types and locations in 10% LID replacement scenario.

Figure 4.9 shows the locations and types of the LID components which are considered to implement the scenario of 15% LID replacement.

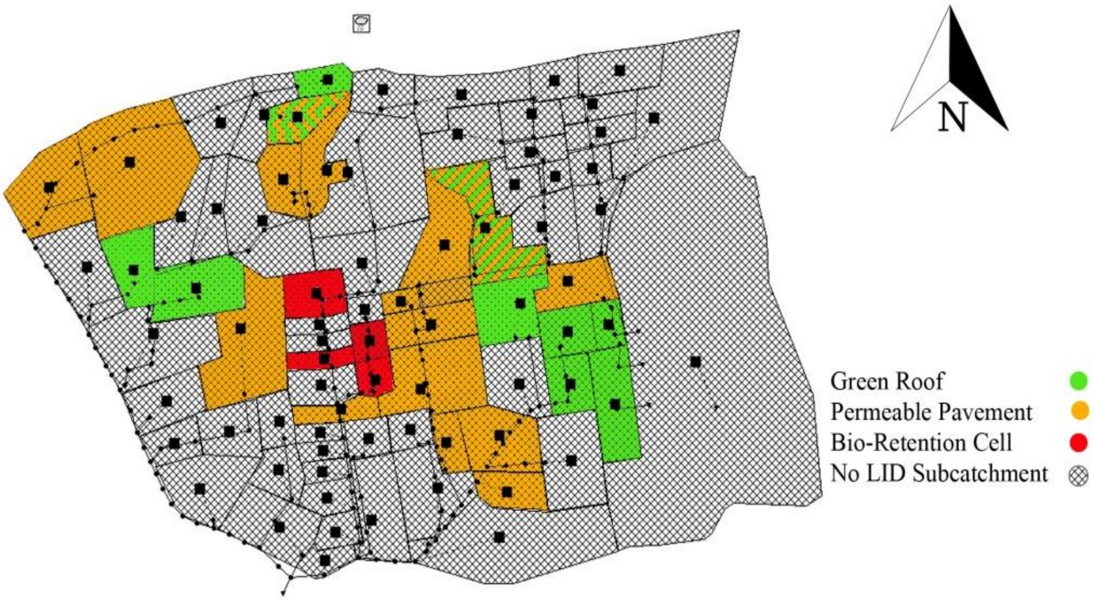


Figure 4.9: Visual map of different LID types and locations in 15% LID replacement scenario.

Figure 4.10 shows the locations and types of the LID components which are considered to implement the scenario of 20% LID replacement.

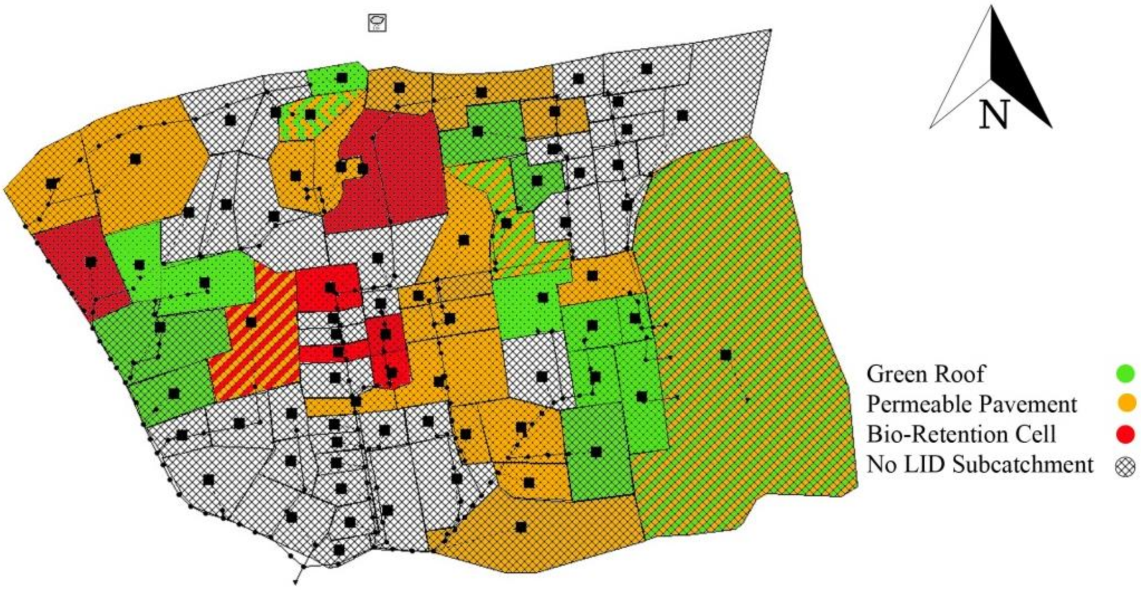


Figure 4.10: Visual map of different LID types and locations in 20% LID replacement scenario.

4.5 Rain Gage:

Rain gages supply precipitation data for a single part or whole of the study area. This rain fall data can even be an external .txt file or a user defined time series data. In this model a user defined time series data has used for rainfall data input for the 5 previously mentioned storm events. Also a .txt file for hourly rainfall data for the time period of November 2017 to November 2018 inputted to the rain gage in SWMM model.

Some of the principal input data required for rain gages are:

- Rainfall data type, can be imported as intensity, volume and cumulative volume.
- Recording time interval, hourly or minute based.
- Source of rainfall data, external or user defined.
- Name of the rainfall data source.
- Rain units, can be as MM or IN.

In this model two type of rainfall data has used for the simulations.

- Single event rainfall data: five storm events with the return periods of 2, 5, 10, 25 and 50 years and duration of 2 hours considered for the peak runoff and runoff volume reduction assessments.
- Long-term rainfall data: one year rainfall data starting from November 2017 to November 2018, has used for obtaining the drainage system annually discharge volume. This amount of discharged water can be save by constructing an appropriate pond at the system main outfall point and use for irrigation and similar purposes.

Also for long-term precipitation data a daily temperature data including daily Maximum and Minimum temperatures for the same period (November 2017 to November 2018) inputted to the model. This temperature data will use for evaporation calculations by SWMM.

Single event storm data entered to the model as a time series with duration of 2 hours and intervals of 10 minutes and according to a normal distribution function with a mean of 0 and standard deviation of 2.

Figure 4.11 shows the shape of the 5 storm events with different intensities and return periods modeled in SWMM.

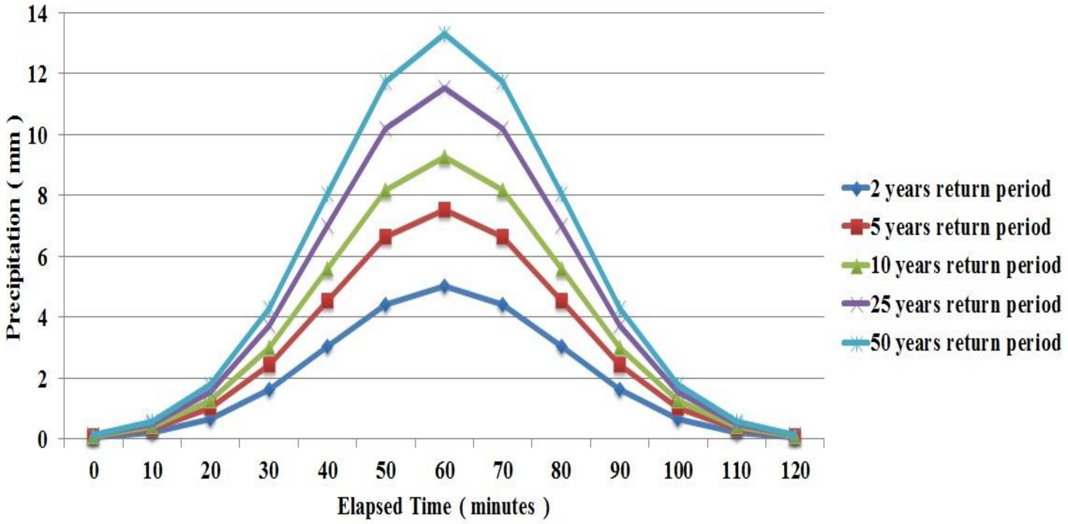


Figure 4.11: Precipitation data for five rain storms with different return periods.

5. RESULTS AND DISCUSSIONS

In this chapter of the thesis the simulation of rainfall-runoff and flow routing models for the study area under different rain storm events and also for different LID replacement usages will be investigated and the results will be demonstrated with tables and figures.

Also as an example, comparison of runoff and inundation situations between before the LID implementations and after the LID implementations in the study area, the effects of LID implementations in the site on runoff reduction under different rain storm events and 10% LID replacement model results will be demonstrated by visual map concepts.

Additionally a long term rainfall data will be simulated in the model to calculate the flow discharge at outfall points of the drainage system. This approach will assist decision makers who plan to construct irrigation ponds in the study area by forecasting the discharge volume to the perspective ponds.

For model calibration and validation the location of measurements and the results also will be shared in this chapter.

This model tried to achieve the reduction rate in peak runoff, runoff volume and also number of ponded nodes by replacing 5%, 10%, 15% and 20% of the impervious surfaces with 3 types of LID control elements. These LID control elements as mentioned before are Green Roof, Permeable Pavement and Bio-Retention Cell. These LIDs contributed together with different ratios to build up the above mentioned percentages of surface replacement. Each LIDs contribution amount decided and specified based on the feasibility and the efficiency of them and also the condition of availability in the campus area.

Also it is tried to locate them at the sub catchments with a higher ratio of runoff contribution.

5.1 Model Validation And Calibration:

Every numeric model has to be calibrated and validated to ensure the accuracy and efficiency of modeling. Validation and calibration were done to determine the validity and accuracy of the rainfall-runoff and flow routing model in this study. For this purpose an analog rain gauge made by TFA Dostmann GmbH & Co.KG Company prepared. Also a meter for measuring the water depth in the manhole used in this process. One manhole locating at the downside of the study area which connects most of the drainage system conduits selected for this purpose.

Figure 5.1 shows the location of measuring point in the study area.

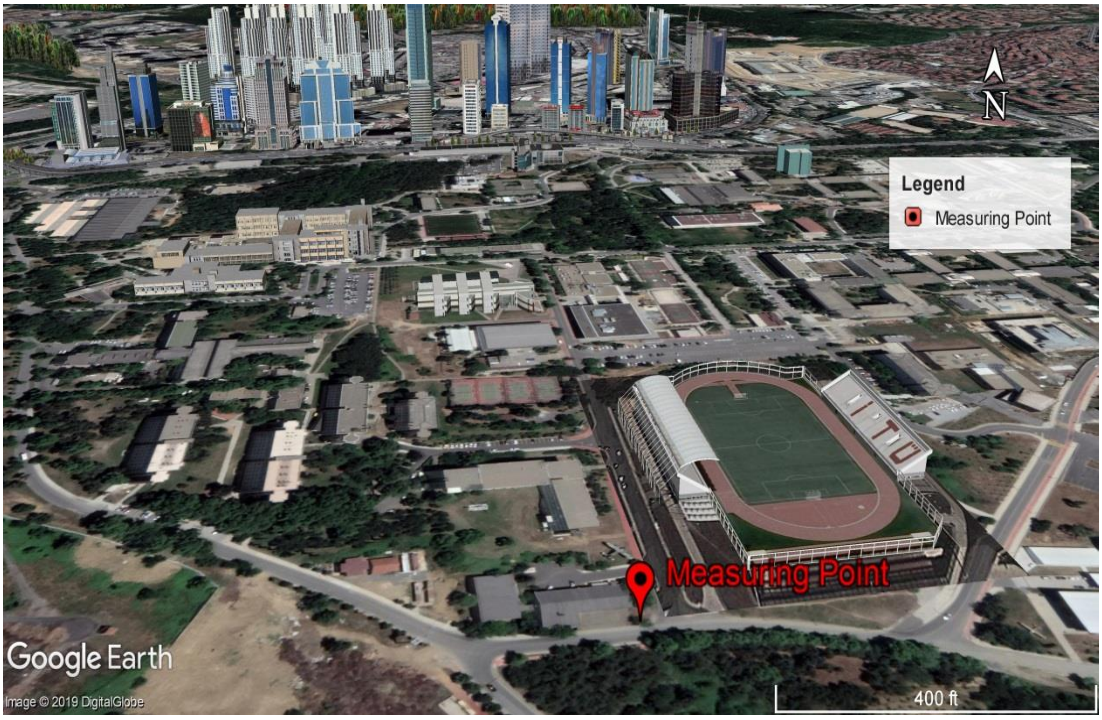


Figure 5.1: The location of measuring point in the study area.

During one rainy day the rain guage installed at a suitable point beside the measuring manhole and at the same time the precipitation amount and the water depth inside the manhole measured and recorded with 15 minutes intervals. It is noteworthy to mention that all of this measurement process done by the author of this report and with high precision.

Figure 5.2 shows the measurement process at the mentioned point.

Figure 5.2: Precipitation and water depth measurement process.

From the precipitation measurements and records, total cumulative rain fall obtained 3.15 mm for the specific rainfall event. Figure 5.3 shows the values for precipitation, simulated water depth at the manhole by SWMM and measured values for the water depth at the manhole according to the time.

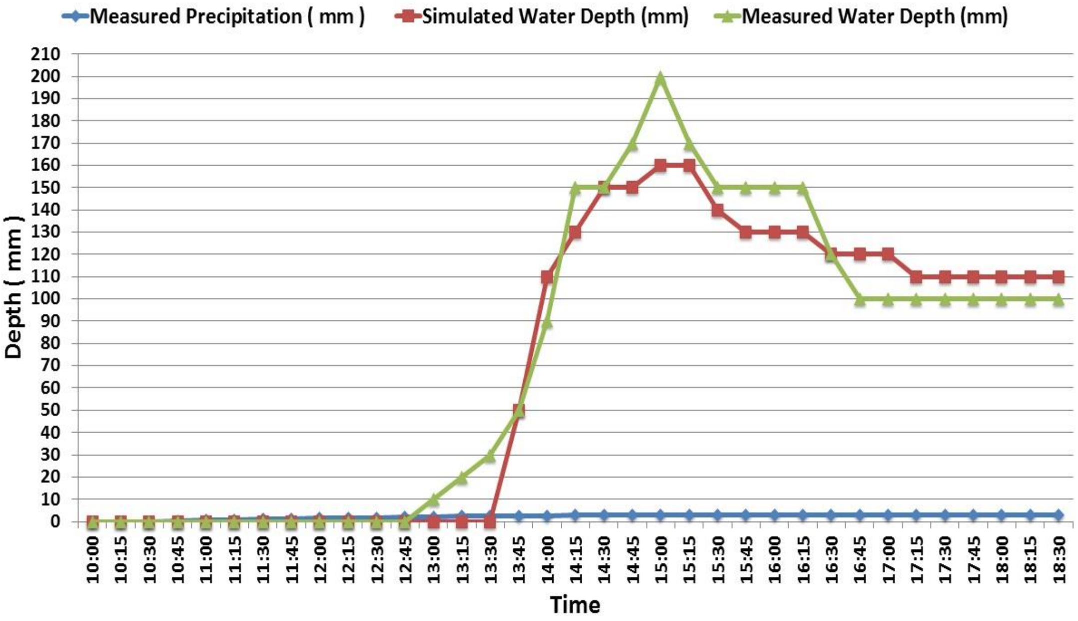


Figure 5.3: Values of measured precipitation, simulated water depth and measured water depth in (mm).

Root Mean Square Deviation (RMSD) method used for calculating the difference between the values simulated in SWMM for water depth at manhole and those measured at the field.

RMSD formula is given below:

$$\text{RMSD}=\sqrt{\sum_{i=1}^{n}(\text{Vi}-\text{Wi})^2/_{n}} \qquad (5.1)$$

Where Vi and Wi are the measured and simulated values for the water depth at the manhole at the time i and n is the number of measured time intervals.

From these calculations the RMSD value for the measurements obtained 14.142 (mm).

For reducing this difference amount, several investigations and tests done based on modifying some of the parameters of native soil and Manning’s roughness for the several surfaces of the study area and finally the calibrated values obtained and tested in the model. Figure 5.4 shows the comparison figure for final simulated water depths at SWMM by using the calibrated parameters and measured values at the field.

Detailed information about initial and calibrated parameters presented at the data chapter of this report. (Table 2.1).

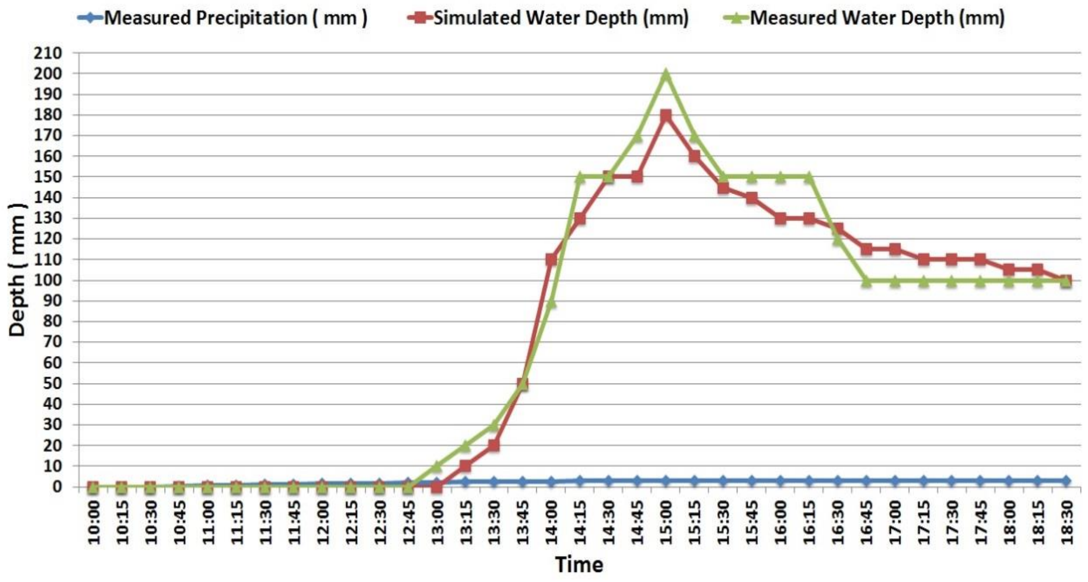


Figure 5.4: Values of measured precipitation, simulated water depth after calibration and measured water depth in (mm).

From the formula mentioned above (5.1), the RMSD value in this try obtained 10.35 (mm) which is relatively good value for this simulation, and the model parameters will input to the model according to the calibrated values.

5.2 Event Based Analyses:

The first part of the model results dedicated to describing the performance of rainfall-runoff and flow routing model of the study area under five different rain storm events that have the return periods of 2, 5, 10, 25 and 50 years and quantify the effects of four different LID usages: 5%, 10%, 15% and 20% on peak runoff and runoff volume reduction.

To present the model results two visual maps were used. While the first one shows the sub catchment runoff, water depth at nodes and flowrate in the conduits for no development condition in the catchment, the second figure shows the results for the 10% LID implementation. The model gives water depths and flowrate results changing with time. The model results are given for the most critical conditions in each analyze which means the highest values of: sub catchments runoff (m^3/s), water depths in nodes (m) and highest flowrate in the conduits (m^3/s).

5.2.1 Storm scenario for 2-year return period:

A rain storm with 2-year return period simulated in SWMM for the study area. Detailed information about precipitation data of each storm event presented at the model preparation chapter (chapter 4) of this report. This rain storm was inputted to the model as rainfall time series that has a distribution of its values over time fitting to the normal distribution function.

At the first step, the study area without LID implementations modelled in SWMM and then 5% of the impervious surfaces replaced by the LID implementations. This procedure continued by adding 5% combination of LID components to the previous step until reaching 20% LID replacement.

Figure 5.5 shows the peak runoff and runoff volume reduction due to the various LID implementation scenarios in the study area for outlet point of the study area and under a rain storm event with 2 years return period.

As it is obvious from the runoff comparison graph, figure 5.5 below, the peak runoff occurs 80 minutes after the rainfall begins, also considering the precipitation data (figure 4.11) and system runoff for the study area under a 2-year return period storm event, the hydrograph Lag time for this try obtained 20 minutes.

Although different LID implementation scenarios have effective and noticeable effects on peak runoff and runoff volume reduction in all of the storm event analyses, there was not a remarkable change in time to peak delay value due to the smaller watershed area and type of the implemented LID components.

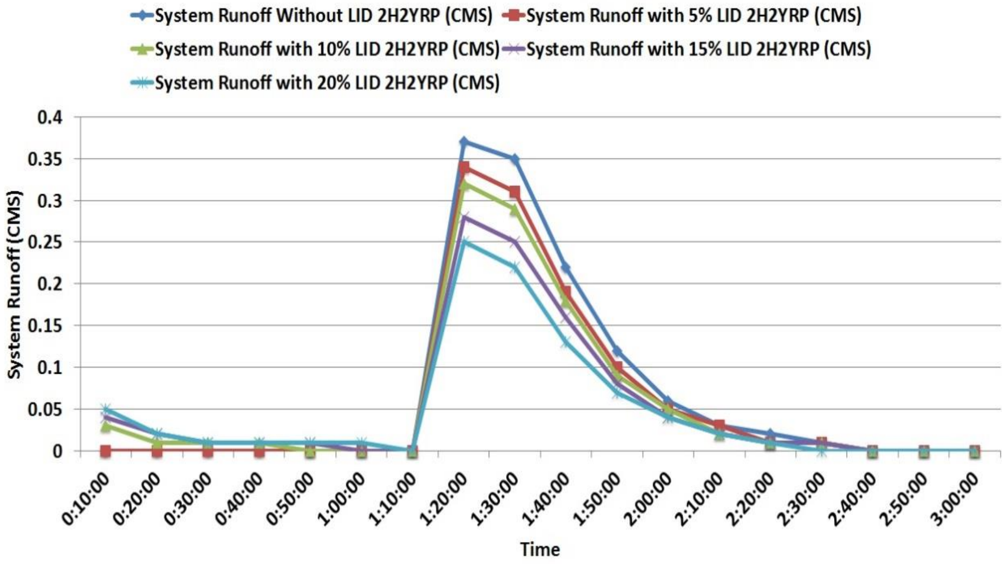


Figure 5.5: System runoff for the study area under a 2 years return period rain storm event and for different percentages of LID implementations.

From the model results the exact amount of peak runoff and runoff volume reduction obtained and presented in Table 5.1.

Table 5.1: Peak runoff and runoff volume reduction percentage in a rainfall storm event with 2 years return period.

	Peak Runoff Reduction Percentage	Runoff Volume Reduction Percentage
Study Area With 5% LID Implementation	8.10	9.85
Study Area With 10% LID Implementation	13.51	12.13
Study Area With 15% LID Implementation	24.32	19.81
Study Area With 20% LID Implementation	32.43	26.86

Figure 5.6 shows sub catchments runoff (m^3/s), water depth (m) at nodes and flow rate (m^3/s) in conduits under a rainfall storm with a 2-year return period and in case there is no LID implementations in the study area.

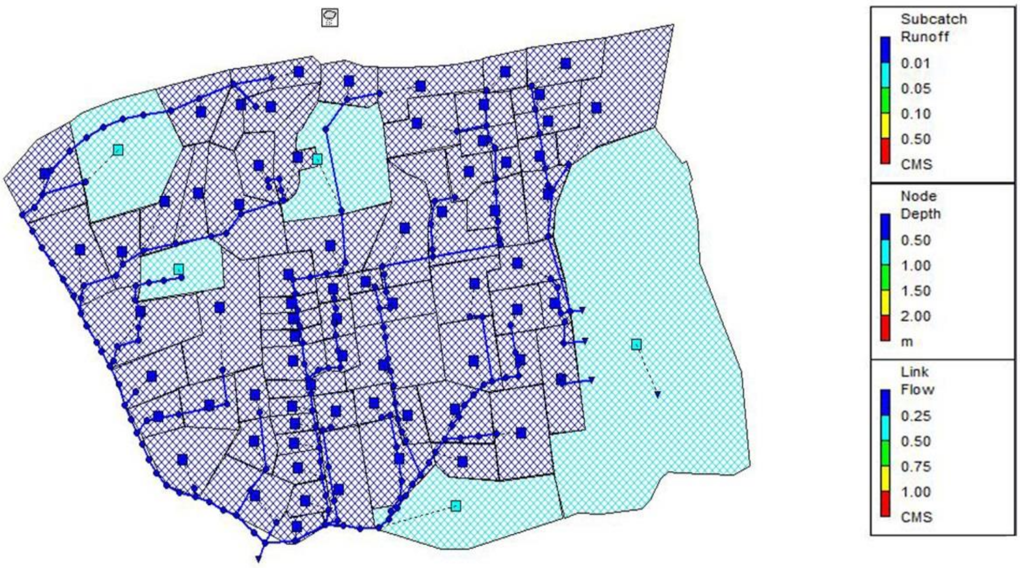


Figure 5.6: Visual map of study area under a 2 years return period storm event and without LID implementations.

Figure 5.7 shows sub catchments runoff (m^3/s), water depth (m) at nodes and flow rate (m^3/s) in conduits under a rainfall storm with a 2-year return period and in case there is 10% LID implementations in the study area.

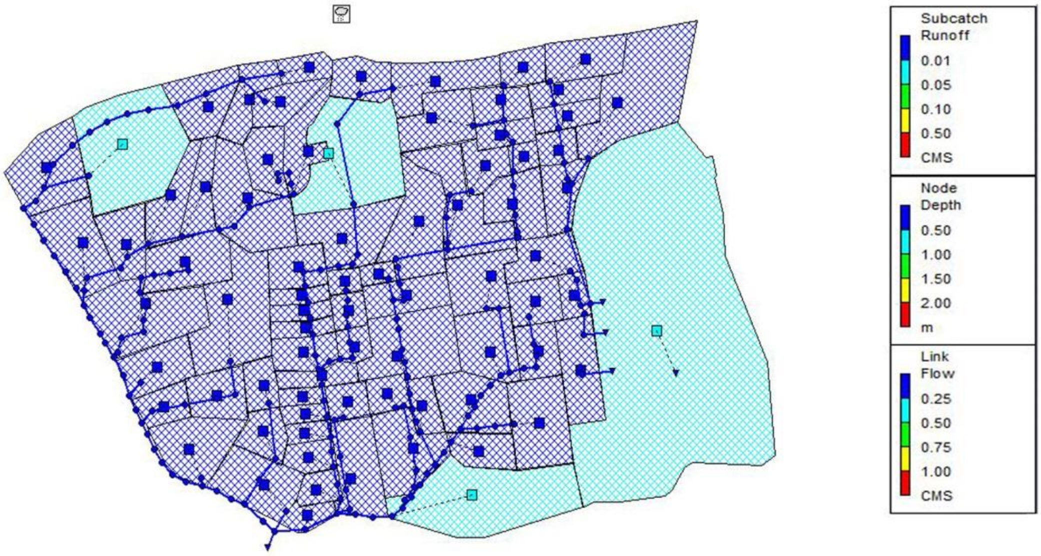


Figure 5.7: Visual map of study area under a 2 years return period storm event and with 10% LID implementations.

Both of the maps in Figure 5.6 and 5.7 are illustrating the situation of the study area at the peak flow moment of the runoff, corresponding to 80 minutes after the rain storm begins.

It can be seen from Figures 5.6 and 5.7 that under the rain storm event with 2 years return period there is no critical situation at the nodes and conduits of the study area and all of them normally collect and conduct the rain water to the system outfall points.

This can be conceived from comparison of the conduits and nodes capacity. The study area conduits diameter varies from 0.3m to 0.6m while the maximum flow depth in corresponding conduits varies from 0.2m to 0.18m in without LID simulations and varies from 0.17m to 0.08m, in with LID implementation simulations.

Also nodes depth in study area varies from 1m to 2m while in without LID simulations maximum depth in nodes raise up to 0.34m in the simulation without LIDs and up to 0.3m in the simulations with LID implementations. Additionally after 10% LID implementations the number of subcatchments with runoff up to 0.05 CMS reduces.

5.2.2 Storm scenario for 5-year return period:

The second rain storm to be assessed, supposed to have a 5-year return period. This rain storm was inputted to the model as rainfall time series that has a distribution of its values over time fitting to the normal distribution function and analyzed in SWMM model for the study area in 5 conditions of without LID implementations and with 5%, 10%, 15% and 20% LID implementations.

The system runoff of these 5 conditions and the reduction in peak runoff and runoff volume obtained from the model results and presented in Figure 5.8 and Table 5.2 below.It is obvious from the Figure 5.8 and from the results that like the try with rain storm with 2 years return period, in this try also peak runoff occurs 80 minutes after rain storm begins. Considering the precipitation data (Figure 4.11) and system runoff for the study area under a 5-year return period storm event, the hydrograph Lag time for this try also obtained as 20 minutes.

Figure 5.8 shows the peak runoff and runoff volume reduction due to the 5%, 10%, 15% and 20% of LID replacement implementations in the study area for outlet point and under a rain storm event with 5 years return period.

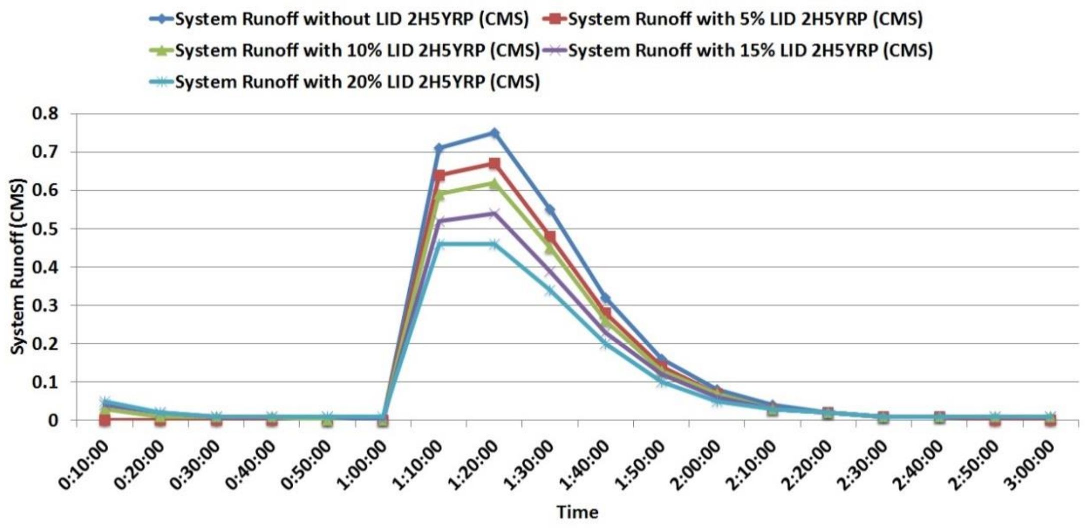


Figure 5.8: System runoff for the study area under a 5 years return period rain storm event and for different percentages of LID implementations.

The exact amounts of peak runoff reduction and runoff volume reduction in this try are presented in Table 5.2.

Table 5.2: Peak runoff and runoff volume reduction percentage in a rainfall storm event with 5 years return period.

	Peak Runoff Reduction Percentage	Runoff Volume Reduction Percentage
Study Area With 5% LID Implementation	10.66	10.51
Study Area With 10% LID Implementation	17.33	14.5
Study Area With 15% LID Implementation	27.5	23.16
Study Area With 20% LID Implementation	37.2	31.60

From the results it can be conceived that although the precipitation increases due to the more intense storm event from 2 years return period to 5 years return period, the reduction rate also increases in the corresponding LID replacement usages for the study area.

Figure 5.9 shows sub catchments runoff (m^3/s), water depth (m) at nodes and flow rate (m^3/s) in conduits under a rainfall storm with a 5-year return period and in case there is no LID implementation in the study area.

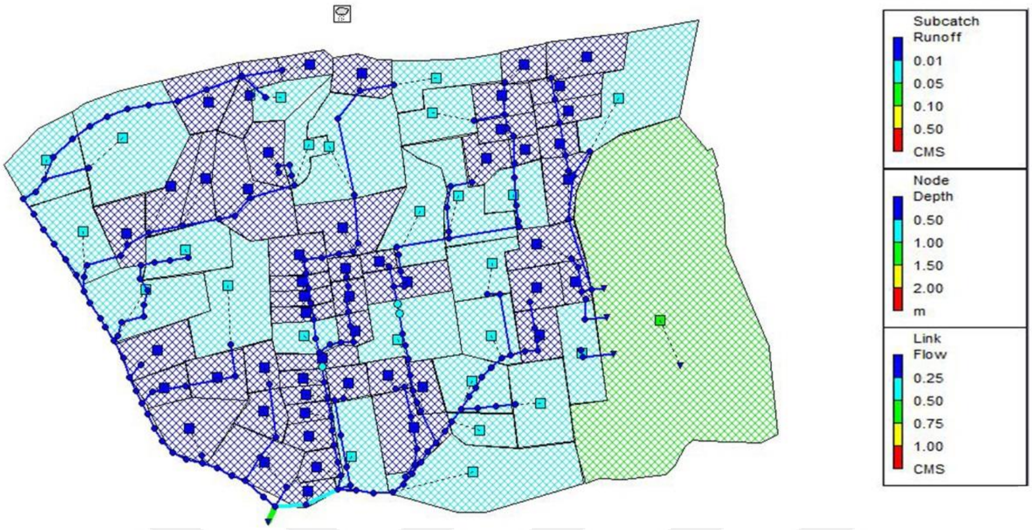


Figure 5.9: Visual map of study area under a 5 years return period storm event and without LID implementation.

Figure 5.10 shows sub catchments runoff (m^3/s), water depth (m) at nodes and flow rate (m^3/s) in conduits under a rainfall storm with a 5-year return period and in case there is 10% LID implementation in the study area.

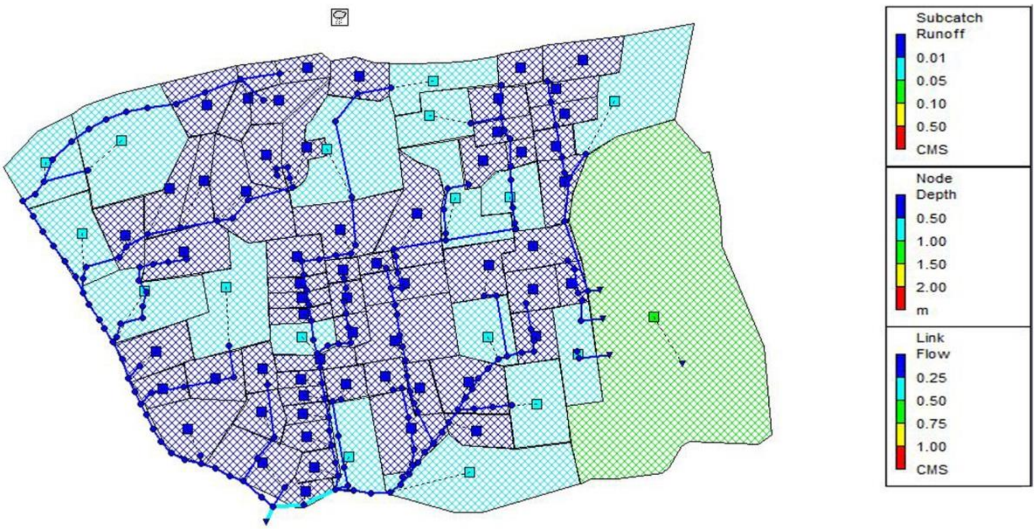


Figure 5.10: Visual map of study area under a 5 years return period storm event and with 10% LID implementations.

Evidently from Figures 5.9 and 5.10 can be recognized that at the storm event with return period of 5 years, like the rain storm event with 2 years return period, yet there is no such a critical situation in the system nodes depth, link flows and sub catchments runoff. Both of the maps above illustrating the situation of the study area at the peak flow moment of the runoff.

This can be conceived from comparison of the conduits and nodes capacity. The study area conduits diameter varies from 0.3m to 0.6m while the maximum flow depth in corresponding conduits varies from 0.28m to 0.34m in without LID simulations and varies from 0.25m to 0.23m in with LID implementations simulations.

Also nodes depth in study area varies from 1m to 2m while in without LID simulations maximum depth in nodes raise up to 0.71m in the simulation without LIDs and up to 0.42m in the simulations with LID implementations.

It is obvious from the colored scheme of the study area that after 10% LID implementations there is noticeable decrease in nodes, links and sub catchments depth, flow and runoff which had higher values before LID implementations.

5.2.3 Storm scenario for 10-year return period:

Third storm event which analyzed in the SWMM model for the study area has 10 years return period and inputted to the model as rainfall time series that has a distribution of its values over time fitting to the normal distribution function.

Like the previous tries, at the first step, the study area without LID implementations modelled in SWMM, under a 10-year return period storm event and then 5% of the impervious surfaces replaced by the LID implementations. This procedure continued by adding 5% combination of LID components to the previous step until reaching 20% LID replacement.

It is obvious from the results of this try which presented in Figure 5.11 below that the peak runoff occurs 70 minutes after the rain begins and this is 10 minutes earlier than the tries with 2 and 5 years return period rain storm event.

Considering the precipitation data (figure 4.11) and system runoff for the study area under a 10-year return period storm event, the hydrograph Lag time for this try obtain 10 minutes.

Also it is possible to recognize the reduction both in peak runoff and runoff volume by observing the figure 5.11 below which demonstrates the system runoff versus time for the outlet point of the study area, regarding the different LID implementation scenarios.

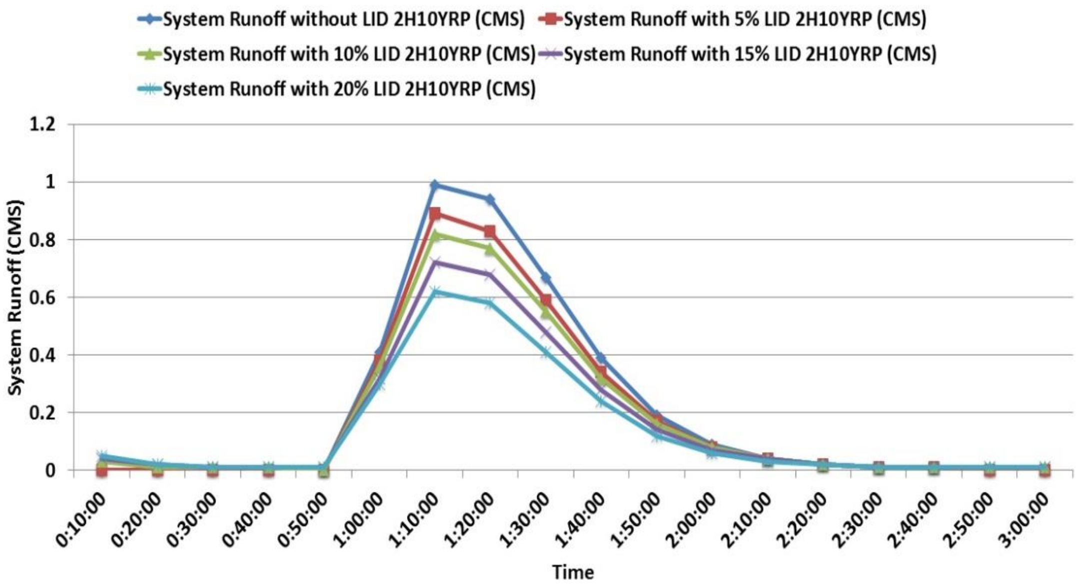


Figure 5.11: System runoff for the study area under a 10 years return period rain storm event and for different percentages of LID implementations.

The exact percentages of peak runoff reduction and runoff volume reduction obtained from model results are presented in Table 5.3.

Table 5.3: Peak runoff and runoff volume reduction percentage in a rainfall storm event with 10 years return period.

	Peak Runoff Reduction Percentage	Runoff Volume Reduction Percentage
Study Area With 5% LID Implementation	10.10	10.5
Study Area With 10% LID Implementation	17.17	15.07
Study Area With 15% LID Implementation	27.27	24.05
Study Area With 20% LID Implementation	37.37	32.83

Figure 5.12 shows sub catchments runoff (m^3/s), water depth (m) at nodes and flow rate (m^3/s) in conduits under a rainfall storm with a 10-year return period and in case there is no LID implementation in the study area.

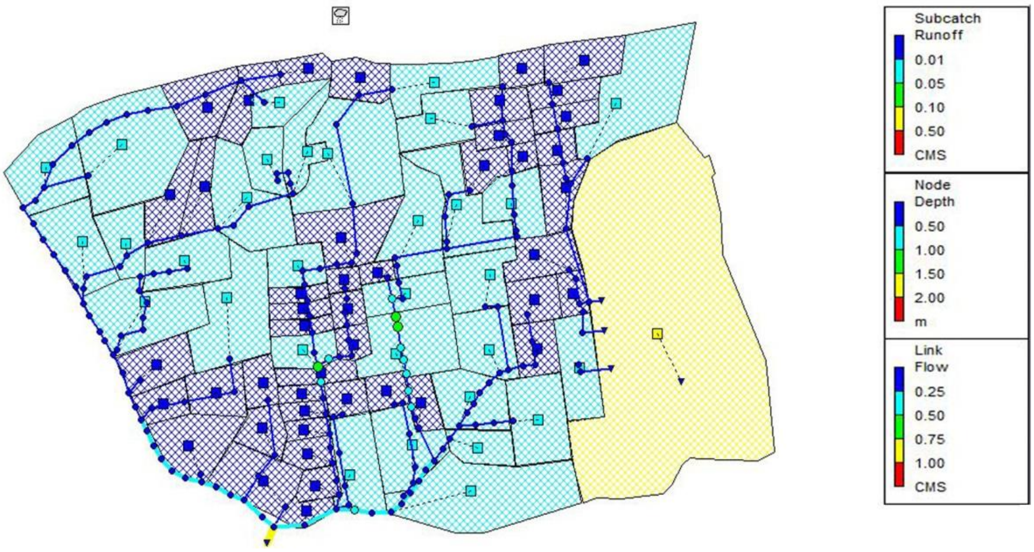


Figure 5.12: Visual map of study area under a 10 years return period storm event and without LID implementation.

Both of the maps are illustrating the situation of the study area at the peak flow moment of the runoff.

Figure 5.13 shows: sub catchments runoff (m^3/s), water depth (m) at nodes and flow rate (m^3/s) in conduits under a rainfall storm with a 10-year return period and in case there is 10% LID implementations in the study area.

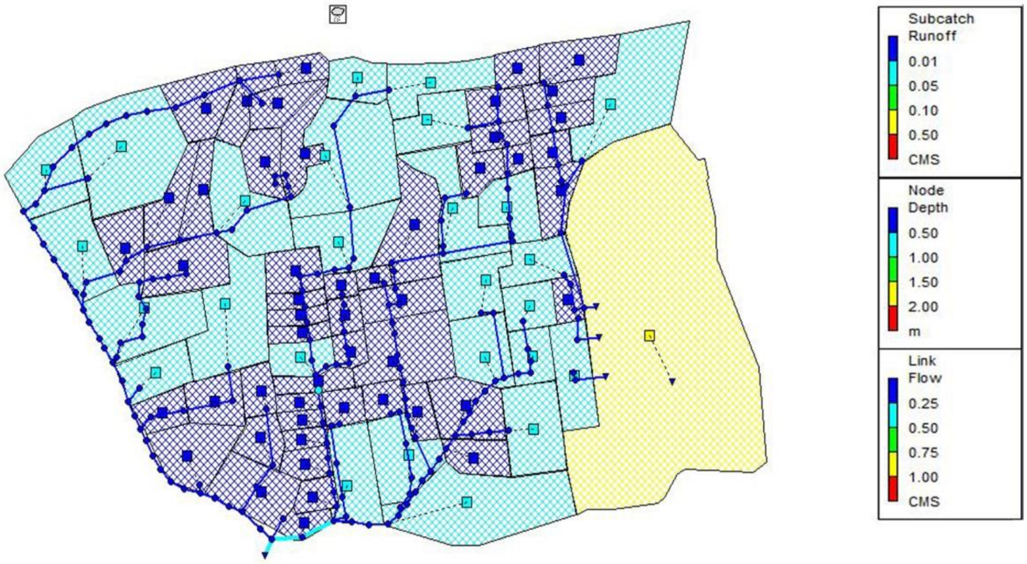


Figure 5.13: Visual map of study area under a 10 years return period storm event and with 10% LID implementation.

It is obvious from the Figures 5.12 and 5.13 that after 10% LID implementations there are reductions in all the aspects of the study area including: nodes depths, conduits flow and sub catchments runoff under simulation with 10 years return period rain storm event. As an example three nodes located at central parts of the study area and identified with green color at the map figure 5.12 have above 1m water height and one of them has already inundated in the simulation without any LID implementations, but after 10% LID implementation the water height in corresponding nodes reduced to about 0.7m and inundation problem resolved.

Also after 10% LID implementations the number of conduits which water depth was reached to the 0.3m, equal to the conduits diameter, reduced from 8 to 2. For the conduits with diameter above 0.3m no pressurized flow observed.

5.2.4 Storm scenario for 25-year return period:

For the fourth analyze a rain storm with return period of 25 years considered and inputted to the model as rainfall time series that has a distribution of its values over time fitting to the normal distribution function. Like the previous tries this analyze also first performed on the study area without LIDs and after, the study area with: 5%, 10%, 15% and 20% LID implementations investigated.

Figure 5.14 below shows the peak runoff and runoff volume reduction due to the various LID implementation scenarios in the study area for outlet point of the study area and under a rain storm event with 25 years return period.

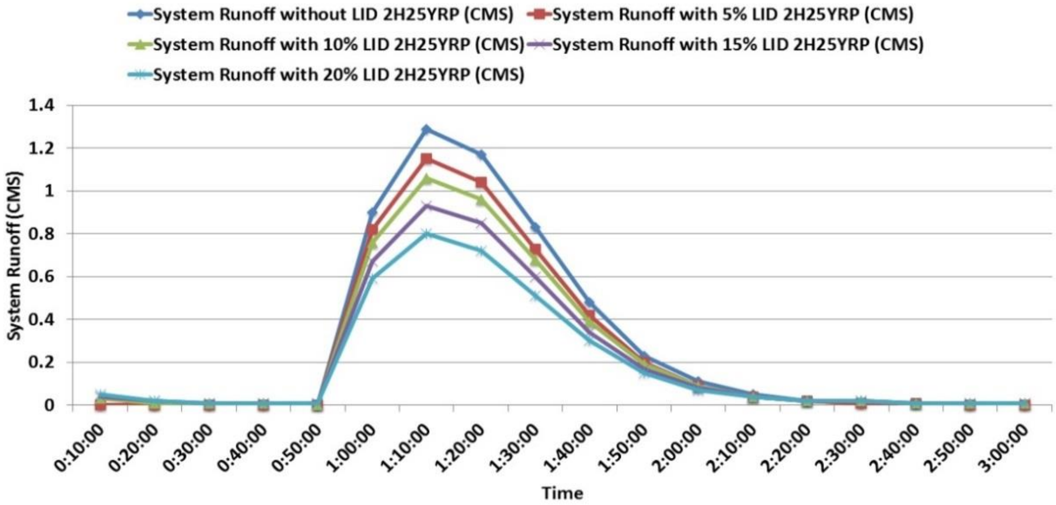


Figure 5.14: System runoff for the study area under a 25 years return period rain storm event and for different percentages of LID implementations.

Obviously from the model results and figure 5.14, the runoff peak flow occurs 70 minutes after rainfall begins which is equal to the try with 10 years return period rain storm event and 10 minutes earlier than the tries with 2 and 5 years return period rain storm events. Considering the precipitation data (Figure 4.11) and system runoff for the study area under a 25-year return period storm event, the hydrograph Lag time for this try obtained 10 minutes.

Table 5.4: Peak runoff and runoff volume reduction percentage in a rainfall storm event with 25 years return period.

	Peak Runoff Reduction Percentage	Runoff Volume Reduction Percentage
Study Area With 5% LID Implementation	10.85	10.76
Study Area With 10% LID Implementation	17.83	15.78
Study Area With 15% LID Implementation	27.9	25.08
Study Area With 20% LID Implementation	37.98	34.33

The exact percentages of peak runoff reduction and runoff volume reduction for this try obtained from model results and presented in Table 5.4 above.

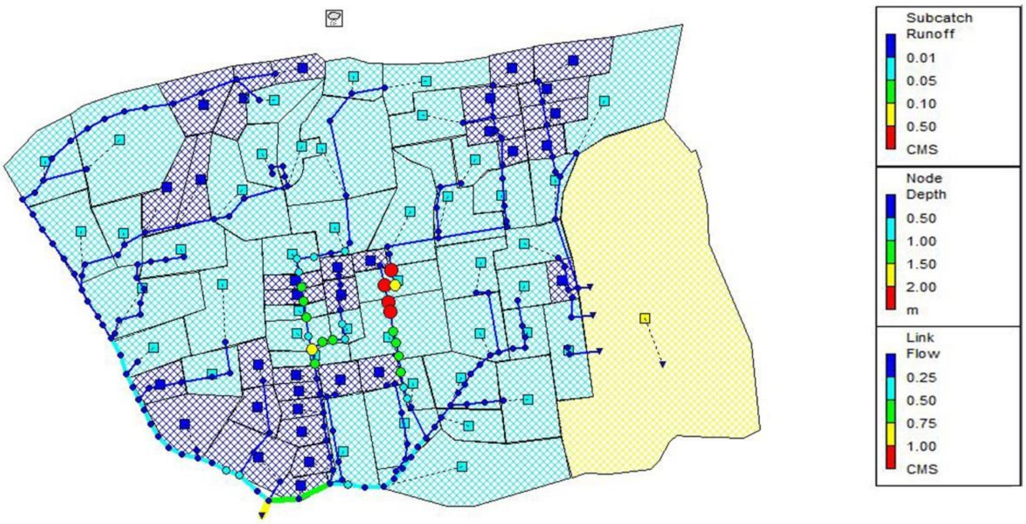


Figure 5.15: Visual map of study area under a 25 years return period storm event and without LID implementations.

Figure 5.15 shows sub catchments runoff (m^3/s), water depth (m) at nodes and flow rate (m^3/s) in conduits under a rainfall storm with a 25-year return period and in case there is no LID implementation in the study area.

Both of the maps in Figures 5.15 and 5.16 are illustrating the situation of the study area at the peak flow moment of the runoff.

Figure 5.16 shows sub catchments runoff (m^3/s), water depth (m) at nodes and flow rate (m^3/s) in conduits under a rainfall storm with a 25-year return period and in case there is 10% LID implementations in the study area.

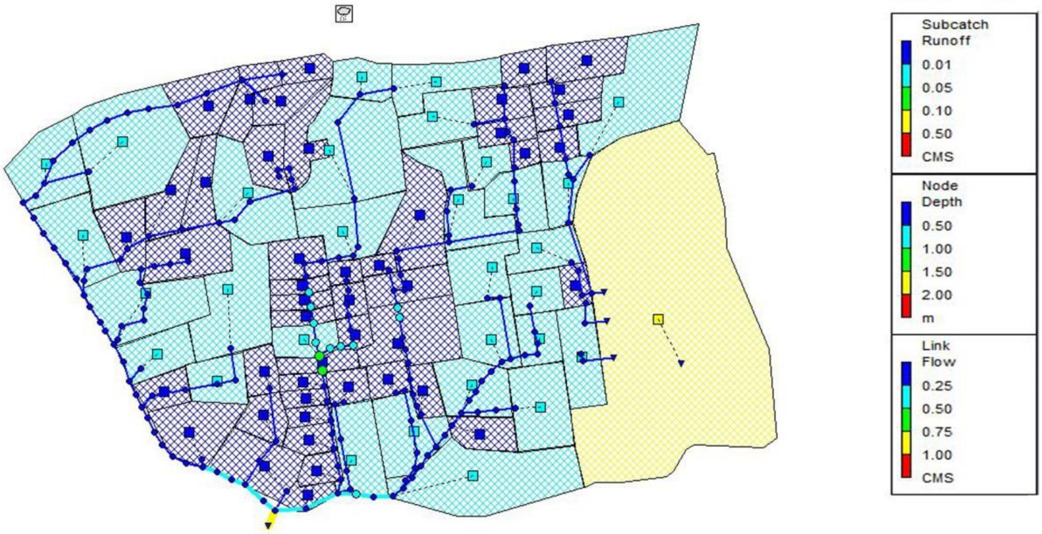


Figure 5.16: Visual map of study area under a 25 years return period storm event and with 10% LID implementation.

Clearly from the Figures 5.15 and 5.16 can be realized that by simulating bigger storm events there will be more critical situations at the study area components like sub catchments, nodes and conduits.

At the mentioned figures above, before LID implementations there are 4 nodes specified with red color which are inundated completely with water depth from 2m to 2.5m. Some other nodes also are inundated specially at central parts of the study area because water depth reached over 1m in them while their maximum depth is 1m. But after 10% LID implementations the number of flooded nodes reduced from 10 to 2 in this try.

Also the conduits carry a noticeable amount of drained water and reached over 0.5 CMS in some parts of the system. After 10% LID implementations the number of conduits which water depth was reached to the 0.3m, equal to the conduits diameter, reduced from 24 to 10. For the conduits with diameter above 0.3m no pressurized flow observed.

5.2.5 Storm scenario for 50-year return period:

The last storm event to be analyzed in SWMM in event based simulations, is a rain storm event with 50 years return period which like the other previous storm events inputted to the model as rainfall time series that has a distribution of its values over time fitting to the normal distribution function. And first performed on the study area without LID implementations and after, performed on the study area with: 5%, 10%, 15% and 20% LID implementations.

Figure 5.17 shows the peak runoff and runoff volume reduction due to the various LID implementation scenarios in the study area for outlet point of the study area and under a rain storm event with 50 years return period.

Obviously from the model results and Figure 5.17 the peak runoff occurs 70 minutes after rainfall begins which is equal to the try with 10 and 25 years return period rain storm events and 10 minutes earlier than the tries with 2 and 5 years return period rain storm events. Considering the precipitation data (Figure 4.11) and system runoff for the study area under a 50-year return period storm event, the hydrograph Lag time for this try obtained 10 minutes.

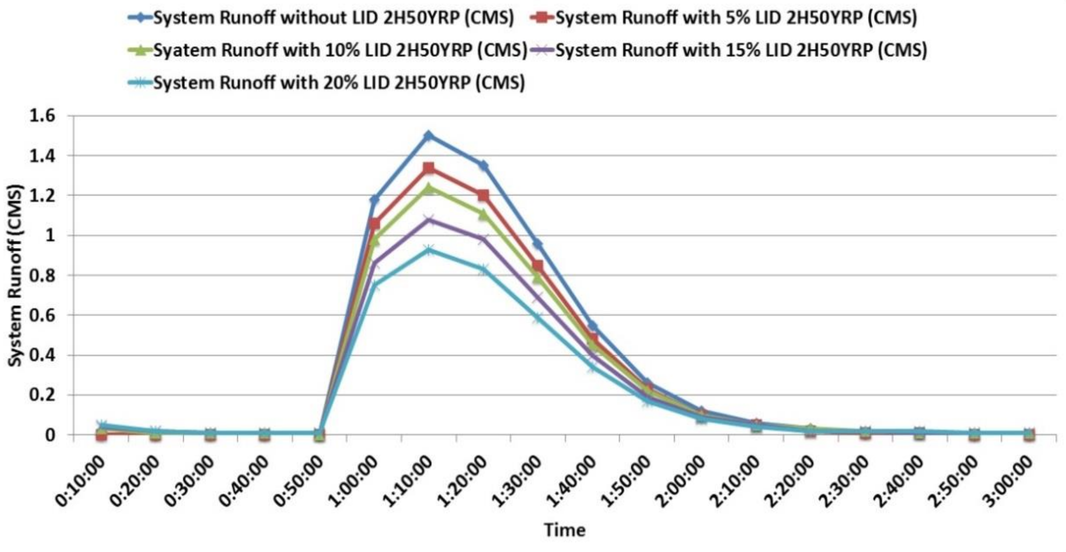


Figure 5.17: System runoff for the study area under a 25 years return period rain storm event and for different percentages of LID implementations.

Table 5.5 presents the exact percentages of peak runoff reduction and runoff volume reduction in the simulation with a rain storm with 50 years return period.

Table 5.5: Peak runoff and runoff volume reduction percentage in a rainfall storm event with 50 years return period.

	Peak Runoff Reduction Percentage	Runoff Volume Reduction Percentage
Study Area With 5% LID Implementation	10.66%	10.92%
Study Area With 10% LID Implementation	17.33%	16.11%
Study Area With 15% LID Implementation	28%	25.5%
Study Area With 20% LID Implementation	38%	34.93%

According to the Table 5.5 it is obvious from the results that the highest reduction both in the peak runoff and runoff volume occurs in the simulation with 20% LID replacement scenario and under 50-years return period storm event condition, with respectively 38% and 34.93% reduction percentages.

Figure 5.18 shows: sub catchments runoff (m^3/s), water depth (m) at nodes and flow rate (m^3/s) in conduits under a rainfall storm with a 50-year return period and in case there is no LID implementations in the study area.

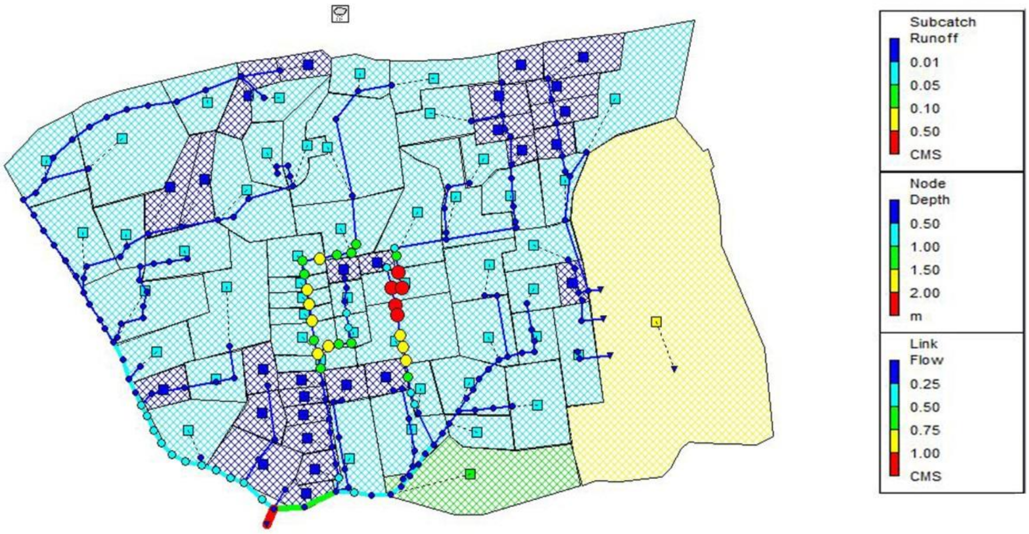


Figure 5.18: Visual map of study area under a 50 years return period storm event and without LID implementation.

Figure 5.19 shows: sub catchments runoff (m^3/s), water depth (m) at nodes and flow rate (m^3/s) in conduits under a rainfall storm with a 50-year return period and in case there is 10% LID implementations in the study area.

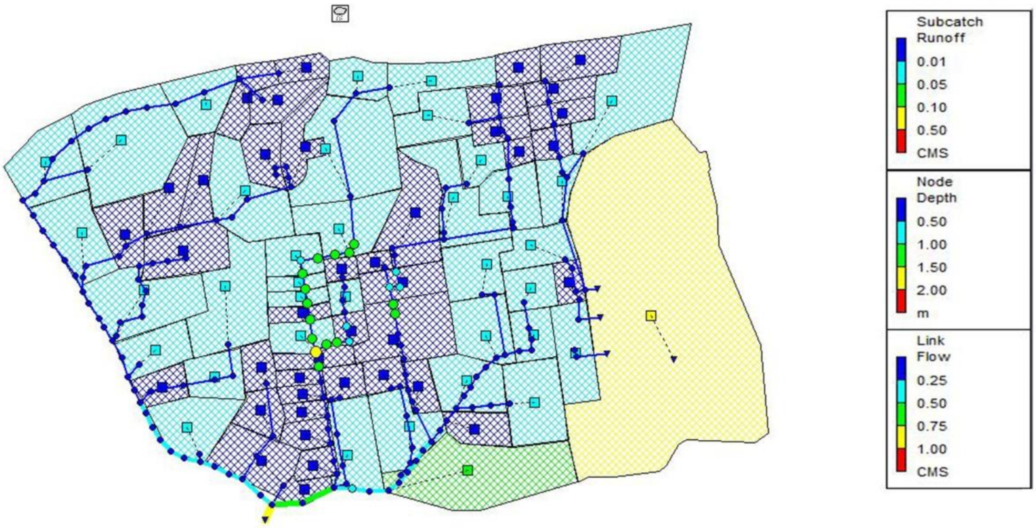


Figure 5.19: Visual map of study area under a 50 years return period storm event and with 10% LID implementation.

Evidently from Figures 5.18 and 5.19, it can be conceived that almost all of the study area is now under a significant flood risk due to the number of flooded nodes and nodes which are at the edge of being flooded, conduits flow rate and sub catchments runoff which are much higher related to the previous storm event simulations.

Five nodes identified with red color at the Figure 5.18 are inundated because of reaching the water depth to over 2m in them also some of the nodes specified with yellow and green colors are inundated because water depth in them reached over 1m while their maximum depth is 1m. After 10% LID replacement as it is obvious from Figure 5.19 red nodes turned to the green and blue ones indicating the water depth now is below 1.5m in them and they are not flooded now. Also in the nodes with maximum 1m depth after 10% LID replacement the number of flooded nodes reduced from 11 to 7.

For the conduits of the study area before 10% LID implementations, 40 conduits were in pressurized flow condition while after 10% LID implementation this number reduced to 20.

5.3 LID Usage Based Analysis

The impacts of different LID replacement scenarios which is mentioned before as: 5%, 10% 15% and 20% on peak runoff and runoff volume for rain storms with 2, 5, 10, 25 and 50 years return periods are investigated in this chapter of the thesis and results are presented in Figures 5.20 and 5.21.

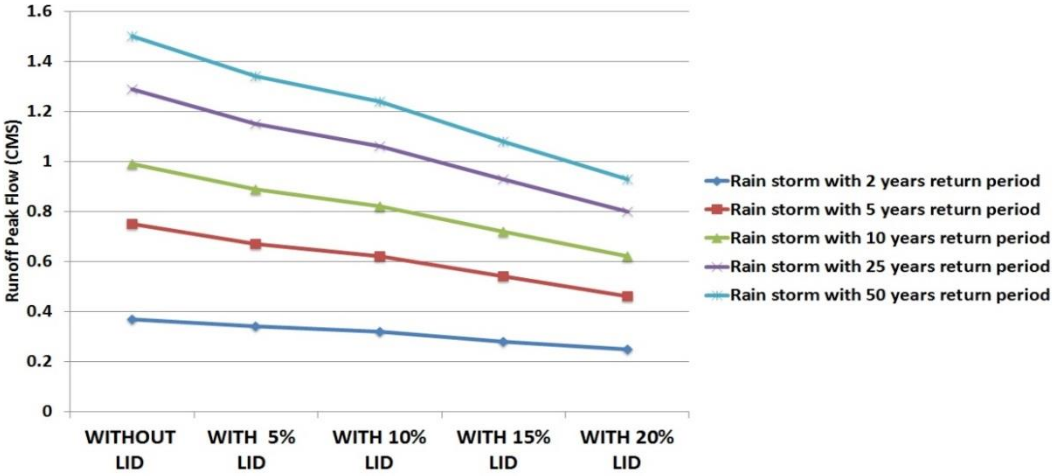


Figure 5.20: Peak runoff reduction due to the different LID usages and for different storm events.

From the Figure 5.20 and by using curve fitting method in Excel program, the relation between peak runoff value and LID replacement percentages and also the coefficient of determination (R^2) in simulation with different rain storm events obtained as Table 5.6 below:

Table 5.6: The relations between peak runoff value of different storm events and the LID replacement percentages and Coefficient of Determination (R^2).

Storm event	Equation	Coefficient of Determination (R^2)
Storm event with 2-years return period	$Y= -0.03X+ 0.402$	$R^2 = 0.9912$
Storm event with 5-years return period	$Y= -0.071X+0.821$	$R^2 = 0.9947$
Storm event with 10-years return period	$Y= -0.091X+1.081$	$R^2 = 0.9968$
Storm event with 25-years return period	$Y= -0.12X+1.406$	$R^2 = 0.9964$
Storm event with 50-years return period	$Y= -0.14X+1.638$	$R^2 = 0.9955$

Where Y is the peak runoff (CMS) and X is the LID replacement usage (%).

Evidently from the Figure 5.20 and obtained equations, the maximum peak runoff reduction obtained with a value of 38% for the simulation with storm event with 50 years return period and in case 20% of the total impervious surfaces of the study area replaced with combination of LID implementations.

It is possible to predict further reductions as LID usages increase up to 30%, 40% and 50% by using trendline forecasting in Microsoft Excel program. For the mentioned percentages in LID usages increase, there will be respectively 56%, 73% and 92% reduction in peak runoff in the try with 50 years return period rain storm event.

However these percentages of LID implementation are not applicable and are far from reality due to the site condition and limited possible area for LID implementations.

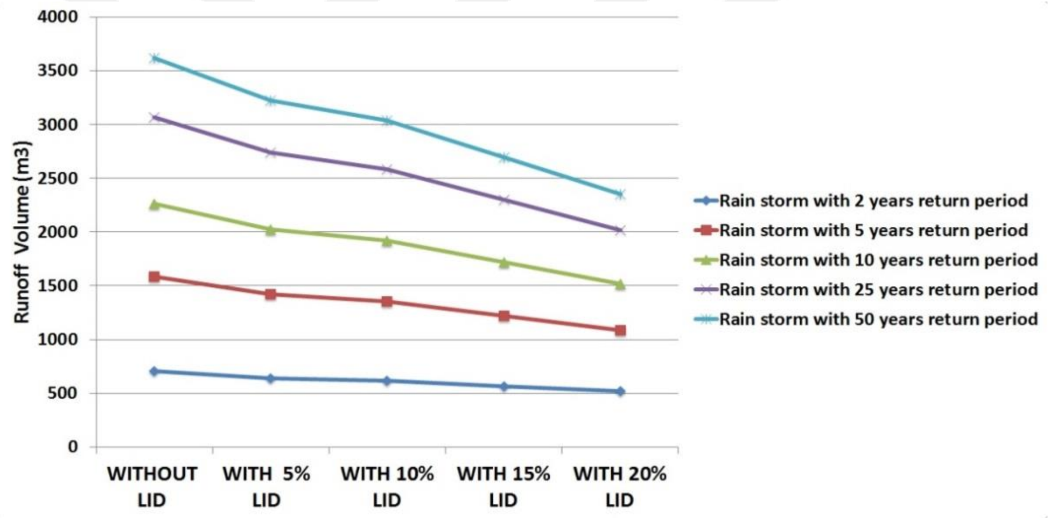


Figure 5.21: Runoff volume reduction due to the different LID usages and for different storm events.

Likewise the peak runoff reduction due to the increase of LID replacement usages and for simulation with different rain storm events, runoff volume also reduced for the SWMM model of the study area by increasing the LID percentage of replacement and for a more intense rain storm event.

From the Figure 5.21 and by using curve fitting in Excel program, the relation between runoff volume value and LID replacement percentages and also the coefficient of determination (R^2) in simulation with different rain storm events obtained and presented in Table 5.6.

Table 5.7: The relations between runoff volume of different storm events and the LID replacement percentages and Coefficient of Determination (R^2).

Storm event	Equation	Coefficient of Determination (R^2)
Storm event with 2-years return period	$Y= -44.954X+743.75$	$R^2 = 0.976$
Storm event with 5-years return period	$Y= -120.26X+1693.5$	$R^2 = 0.9868$
Storm event with 10-years return period	$Y= -179.08X+2424.7$	$R^2 = 0.9897$
Storm event with 25-years return period	$Y= -254.77X+3306.4$	$R^2 = 0.9909$
Storm event with 50-years return period	$Y= -305.41X+3900.9$	$R^2 = 0.9913$

Where Y is the runoff volume (m^3) and X is the LID replacement usage (%).

Obviously from the Figure 5.21 and obtained equations, Maximum runoff volume reduction due to the model results obtained with a value of 34.93% and for the simulation of a rain storm event with 50 years return period and by implementation of 20% LID facilities in the study area SWMM model. It is also possible to predict further reductions as LID usages increase up to 30%, 40% and 50% by using trendline forecasting in Excel program. For the mentioned percentages in LID usage increase, there will be respectively 51.6%, 68.2% and 84.8% reduction in runoff volume in the try with 50 years return period rain storm event.

However these percentages of LID implementation are not applicable and are far from reality due to the site condition and limited possible area for LID implementations.

5.4 Long Term Evaluation:

The last analyze in this thesis project dedicated to investigating the amount of discharge from the drainage system outfall points. This analyze done based on an annual precipitation data and with purpose of obtaining the retainable discharge amount from drainage system, which the main part of it already lost from the system’s main outfall point by releasing into the sea with ISKI made canalization and the rest parts collect in ITU gölet.

For this analyze, one year long precipitation data starting from November 2017 until November 2018 has used. For the same period the temperature data was also used for evaporation computations.

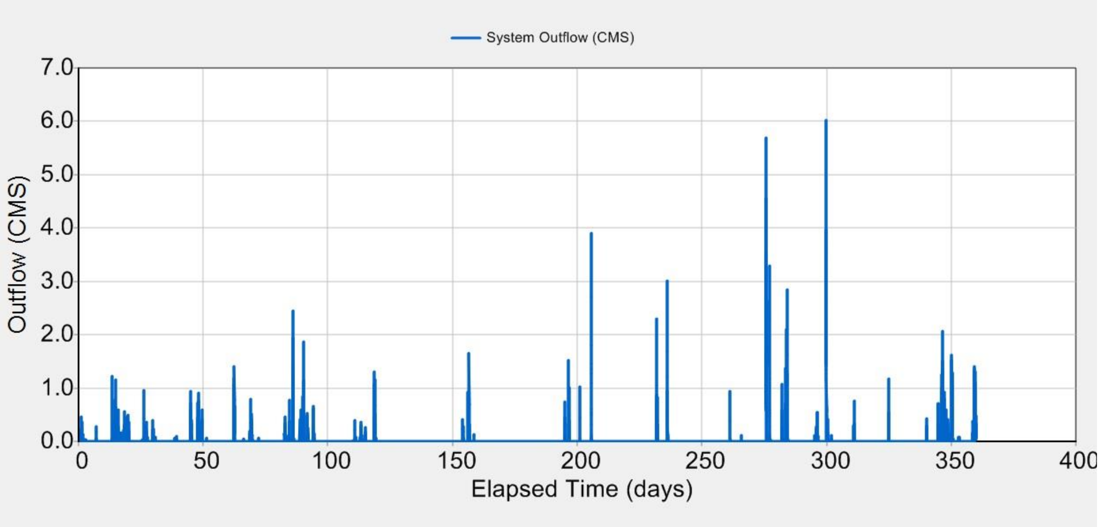


Figure 5.22: Daily system outflow (CMS) during one year simulation for the study area.

It is assumed that by redirecting the drained water, at the system main outfall point and conducting to a suitable retain pond it will be possible to save noticeable amount of water which can be used for irrigation or similar purposes.

Figure 5.22 presents the daily discharge exiting from the system and entering the conduits ended in Bosporus. The simulation period is from November 2017 to November 2018.

Based SWMM model statistics and outflow calculations, in total: 914,544 m^3 drained rain water lost from the system for simulated time period from 2017 to 2018. By constructing a suitable retention pond at the main outfall node of the system this amount of water can be saved and used in irrigation and similar purposes.

6. CONCLUSIONS

In this study the effects of three kinds of LID practices including Green Roof, Permeable Pavement and Bio-Retention Cell on the peak runoff and runoff volume reduction investigated via four scenarios of implementing a combination of these LID components as 5%, 10%, 15% and 20% replacement percentages on the impervious surfaces of Istanbul Technical University main campus.

Five different rain storms with 2, 5, 10, 25 and 50 years return period analyzed in this investigations and the amount of reduction and relation between LID replacement percentages in these storm events obtained. According to the results in these investigations, the reduction rate in peak runoff and runoff volume has a linear relation with LID replacement percentage for different storm events and increases with a bigger storm simulation and by a higher LID replacement percentage.

The slope of the linear relation between peak runoff and LID replacement percentage obtained as: -0.03, -0.071, -0.091, -0.12 and -0.14 respectively for the storm events with 2, 5, 10, 25 and 50 years return period, showing that proposed LID implementations will lead to higher reduction rate for peak runoff for the storm events with higher return periods. Also for the slope of the linear relation between runoff volume and LID replacement percentage the values obtained as: -44.95, -120.26, -179.08, -254.77 and -305.41 respectively for the storm events with 2, 5, 10, 25 and 50 years return period, showing that proposed LID implementations will result in a higher reduction rate for runoff volume for the storm events with higher return periods.

The (R^2), value for these equations obtained above 0.9 in all analysis, showing a good agreement between the obtained values of simulation with the linear relationship of the LID replacement percentage and reduction rate in peak runoff and runoff volume.

The maximum reduction rate obtained in simulation with a 50-year return period rain storm and in case there is 20% LID implementations in the study area with a value of

38% for peak runoff and 34.93% for runoff volume. Also from the flow routing model results, it is concluded that implementing mentioned LID components even in case of 10% replacement, a noticeable number of nodes and conduits of drainage system will not face inundation and flooding in the storm events with 10 and specially 25 and 50 years return period and this will lead to resolving the need of increasing the pipe diameters in the future.

From long term rainfall analyzing results it obtained that 914,544 m^3 water discharges from the drainage system outfall point annually which in case of constructing a suitable retention pond this amount of water can save and utilize for irrigation and similar purposes.

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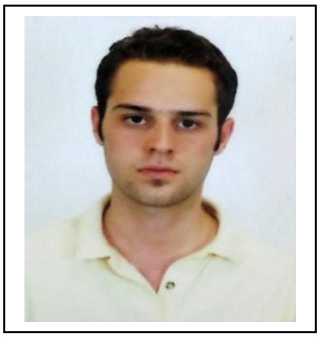

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