Master Thesis

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Bluegreengrey (BGG) solution for future climate and flood-resilient urban drainage network by enhancing the natural hydrological cycle

A case study in a District in Trelleborg, Skåne, Sweden

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Acknowledgment/Preface

I named Adnan Asif Rifat wrote this master's thesis as the last job to conclude my master's program in water resources engineering at Lunds Tekniska Högskola (LTH) which is a part of Lund University. This thesis was done under SPARC, a research project founded by FORMAS (the Swedish Research Council for Sustainable Development) during the Spring of 2023.

First, I would like to thank my supervisor Shifteh Mobini for choosing me to conduct my master's thesis under her supervision. Your inspiration and the way you encouraged me since the beginning and your valuable advice, guidelines, and support throughout all the work with this thesis. Without your support, I could not have gone through this whole work with curiosity and confidence.

Special thanks to DHI for providing me with a license to work with Mike+ to do my thesis work. I would like to extend my special thanks to Maria Roldin from DHI Malmö, my model advisor, for helping me understand the modeling task. This work was the first time for me to model a pipe network system with Mike+ and your support, guidance, and pushing to learn how to solve the problem helped me to understand the model confidently at the end. My thanks must be dedicated to BGG expert Kent Fridell, from EDGE to introduce details and specialty of BGG to me. Without understanding BGG structures and their cross sections it would not be possible to model them for me. Special thank you to Liisi Nogu from Trelleborg Municipality for providing me with all GIS and basement-level data. Tomas Wolf from Trelleborg municipality arranged and provided me with the real rainfall data and organized a study visit to the case study area.

Thank you, Theo Segur, for helping me get back my confidence, guiding me with many writing skills, and for other support during this long work. Thanks to Hugo Lindbäck for your feedback on my thesis.

This thesis journey started with reading articles and journals, which were not easy to summarize, but my supervisor's and friends' support made this reading interesting. However, during my master's study with this program, I met many teachers at school who provided valuable courses to gain knowledge about water and its various mechanisms. Every course at LTH had an assignment or task to do a small project on a relevant course which I found very potential, encouraging, and important for students to be fit for future challenges and assignments in job life. So, I am extending my thanks to all my teachers and the LTH for giving me a fantastic opportunity to conduct my master's in water resources engineering and finish it successfully.

Abstract

A loop of urbanization, increasing impervious surface in urban areas, increasing temperature, rainfall, surface runoff and flooding, and lack of new spaces have been adding challenges to urban drainage systems for decades. The climate change impacts are exposing the existing vulnerable conventional urban drainage systems to more challenges in the future. A new idea of sustainable drainage system named Bluegreengrey (BGG) which was introduced by EDGEs brings a solution to retrofit the existing landscape and drainage system in a more efficient way to detain stormwater in open subbase layer of existing roads and use it for more healthy green lives in urban areas while solving the basement flooding problem.

In southern Sweden, downpouring will be frequent due to climate change, which threatens existing drainage systems in urban areas and may lead to more basement flooding. In this study, a district in Trelleborg municipality in the south of Skåne, the southernmost county of Sweden, experiencing repeated basement flooding for a long time was investigated with BGG structures to test their performance to mitigate basement flooding in this area. Incorporating BGG with proper settings of existing LID tools in the model software Mike+ was one of the outcomes of this study. Mike+ is a modeling software introduced by DHI.

The hydraulic and physical parameters were chosen as per guidelines for usage of Mike+ and practicing properties of BGG suggested by EDGEs. The porosity of substrate and storage layers and the infiltration capacity of the top surface layers are the dominant factors to define the capacity of BGG structures. The size and distribution of BGG structures, the formation and size of catchments, and the size of rainfall events cause variations in the surface runoff reduction capacity of BGG structures. By storing stormwater and providing it for trees and plants BGG enhances the natural hydrological cycle in urban areas which was concluded from the stormwater distribution results with BGG deployed in the model. The model was run with a 10-year synthetic rainfall event provided by DHI with a climate factor of 1.25 and then BGG structures were deployed along several roads until they can make the basements of all the households claimed flooding, become free from flood. A real rainfall event of 2021 was provided by the Trelleborg municipality. This real rainfall event recorded in 2021 was found to be equivalent to a 50-year rainfall event. The same model with deployed BGG structures was then tested with this real rainfall event to see their performance with a 50-year rainfall event. The results showed the characteristics of BGG structures to enhance the natural hydrologic cycle and at the same time, flood-claimed households remain out of flood risk.

In this study, BGG structures reduced the surface runoff produced from impervious surfaces in the case area by up to 96% for individual catchments for 10-year rainfall events. The average surface runoff reduction capacity of BGG structures was 48% for the 10-year rainfall. On average the BGG structures infiltrated 0.08m^3/sec, stored 0.37m^3/sec, and produced 0.11m^3/sec runoff when the inflow in the BGG structures was 0.56m^3/sec. Replacement of 14% of the existing impervious surface with BGG in a catchment can reduce the surface runoff by 50% for 10-year rainfall. The deployed BGG structures showed the same performance for 50-year rainfall and reduced the runoff by 48%. As the surface runoff capacity is subjected to the size of BGG structures, catchments, and rainfall it cannot be summarized with any specific number in case of reduction capacity. BGG structures were found in this study to reduce the discharge rate and flow velocity through the pipes. The discharge rate and flow velocity through the outflow pipe indicate a smoother flow discharge which is good for the downstream recipients and biodiversity as well.

The impact of source control or disconnecting impervious surface areas of private lands from the drainage network was also tested in this study. As obvious the runoff volume reduced with reduced impervious surface in the catchments.

KEYWORDS: Bluegreengrey, Sustainable stormwater, Basement flooding, Urban flooding, Pipe Network, BGG, Climate change, Hydrology, Mike+.

LIST OF ABBREVIATIONS

BGG: Bluegreengrey

BMP: Best Management Practices

CL: Climate

CRED: Centre for Research on the Epidemiology of Disasters

CSO: Combined Sewer Overflow

GHGs: Greenhouse Gases

GI: Green Infrastructure

LID: Low Impact Development

OSL: Open Subbase Layer

OSWS: Open Storm Water System

SDGs: Sustainable Development Goals

SMHI: Swedish Meteorological and Hydrological Institute

SUDM: Sustainable urban drainage management

SUDS: Sustainable Urban Drainage System

UNISDR: UN Office for Disaster Risk Reduction

US EPA: U.S. Environmental Protection Agency

WSUD: Water-Sensitive Urban Design

Contents

1. Introduction 1

  1.1 Background 1

  1.2 Aim of the Study 2

2. Theories and Background 3

  2.1 Pluvial Flood in Urban Hydrology 3

  2.3 Climate change impact on Pluvial flooding: 5

  2.4 Sustainable stormwater management: Concept of Sustainable Drainage System 5

    The concept of Bluegreengrey (BGG) 7

  2.5 Site Introduction: 12

  2.6 Mike+ 13

3. Methodology and Materials of the study: 14

  3.1 Methods 14

  3.2 Model Setup and Calibration 16

  3.3 Model set up with BGG. 17

  3.4 Sizing and deployment of BGG structures in the study area 20

  3.5 Boundary condition 22

4. Results and discussions: 23

  4.1 Distribution of BGG structures 23

  4.2 Performance of BGG to reduce the risk of urban flooding and its consequences. 27

  4.3 Capacity of installed BGG structures 31

  4.4 Performance of proposed BGG structures under real rainfall of 2021 32

  4.5 Performance of source control SUDS and compare to BGG 38

5. Limitations 38

6. Conclusion 39

References 40

1. Introduction

1.1 Background

Flooding is one of the most common natural disasters globally which causes casualties, economic losses, increased health risk and cost, severe change or damage in socio-economic status, degradation of the ecosystem, damage to cultural and historical values, and so on (CRED, UNSIDR, 2018). The phenomenon in which an overflow of water inundates the land that is usually not underwater is defined as flood (*What Is a Flood? - Earth Networks*, 2021). The report published by CRED and UNISDR in 2018 named Economic Losses Poverty & Disaster shows flood as the most frequent disaster which is 43.4% of all the recorded disasters from 1988 to 2017(CRED, UNSIDR, 2018). Though 11% of total casualties were caused by floods. But floods and storms combined 69% of total economic loss and 45% of total affected people by disasters happened between 1988 and 2017 (ibid). Though that report was made on only reported disasters and claims of losses, many countries with low income, lack of data collection, storage, technology, and knowledge during the reporting time were out of this report. Due to high population density, and socio-economic and property values flooding in urban areas, stormwater management got the attention of global researchers, planners, engineers, policymakers, and citizens. Rainfall, urbanization, improper or inadequate sewage system, improper waste management, poor engineering design, and works, lack of maintenance, lack of awareness and regulations, consequences of the increase in emission of greenhouse gases (GHGs), climate change, global warming, and many other reasons can cause urban flooding (Asiedu, 2020). A study about economic and social loss by basement flooding or urban flooding in Illinois found that the property value is reduced by 10-15% and almost 40% of small businesses could never overcome the damage caused by basement flooding (Harriet Festing, et al., 2014). They also found that 13% of victims of basement flooding were exposed to illness (ibid). European cities are intended to increase exposure to urban floods with increasing urbanization and climate change impact (Skougaard Kaspersen et al., 2017). Due to the aging of existing drainage systems and their expensive replacement cost, nowadays retrofitting stainable or open stormwater management systems in terms of blue-green and grey solutions is becoming popular in research and practice.

Higher property values and population along with changed land use and drainage system made urban flooding a concern issue globally and as well as for Sweden. Swedish Portal for Climate Change Adaptation(klimatanpassning.se) describes urban flooding in terms of pluvial flooding which most commonly happens in urban areas with increased runoff peaks due to heavy rainfall with a shortened time of concentration. Heavy fall of rain, called a downpour, happens in Sweden, but it is more common in the southern part of the country (*Flooding | Swedish Portal for Climate Change Adaptation*, 2021). This is potentially causing urban or basement flooding in cities in Sweden.

Climate change and global warming will result in an increased temperature and increased humidity, causing more precipitation, especially high-intensity rainfall with short duration and increased frequency which is challenging for urban drainage systems. The Swedish Meteorological and Hydrological Institute (SMHI) expects that climate change’s impact on Sweden will increase extreme precipitation. This heavy rainfall alongside urbanization leads to urban flooding today and it will appear severely in the future. A study on climate change and urbanization’s impact on the drainage system in Helsingborg, Sweden suggested climate change and urbanization either alone or together will increase the risk of a flood (Semadeni-Davies et al., 2008).

Sustainable Development Goals (SDGs) aim to ensure safe drinking water and sanitation for everyone, to combat climate change and its impacts, to disaster risk reduction, to make cities safe, resilient, and sustainable, and to ensure the ecosystem including life on land and underwater (UN, 2015). These goals lead to sustainable flood management and drainage system adaptation to ensure clean and healthy cities along with preserving or improving ecosystems. Ensuring optimal use of available land, participation of stakeholders (citizens), social learning, and a resilient urban system can be considered sustainable urban drainage management (SUDM) (Andreas Persson, 2020). Several strategies named best management practices (BMPs), sustainable urban drainage systems (SUDs), water-sensitive urban design (WSUD), green infrastructure (GI), low impact development (LID), blue-green- grey are being practiced in many cities to ensure clean sustainable cities with sustainable flood management and drainage system.

This study focused on a district in Trelleborg municipality in the south of Sweden in Skåne County. Though this is a coastal city, the district under the case study has a problem with basement flooding which is mainly caused by excess load in the pipe network produced from precipitation. The bluegreengrey (BGG) structures will be used to minimize basement flood loss and risk in the case study area and the efficiency of BGG structures will be analyzed. The concept and mechanism of BGG will be described in later parts.

1.2 Aim of the Study

The municipality of Trelleborg has a historical problem with urban flooding that results in basement flooding in several areas in the city. The municipality is facilitated with both combined and separated sewer systems to manage sewage and stormwater runoff. 3% of the sewer system is combined, and the rest relates to a separate system. Making optimal use of land, road, and existing pipe network systems can reduce the flood risk with the existing landscape along with improved ecosystem and aesthetical view in the city. This study will focus on:

- Analyzing the exposure of the case study area to basement flooding in the future with climate change impact.
- Propose custom settings to incorporate BGG structures in Mike+
- Find a suitable sustainable drainage solution with BGG to make the existing combined pipe network function with a 10-year rainfall event with a climate factor of 1.25.
- Analyze the capacity and efficiency of proposed BGG structures.
- Test and compare the performance of source control (private property-owned sustainable solution) SUDS and BGG.
- Check the model with the suggested solutions with real rainfall data (50-year rainfall) to observe its performance.

2. Theories and Background

2.1 Pluvial Flood in Urban Hydrology

Pluvial flood can be defined as a flood caused by heavy rainfall when the runoff produced by rainfall exceeds the drainage capacity, saturating the urban drainage system which is independent of any overflowing water body (Maddox, 2014). In the natural hydrological cycle, a fraction of the precipitation goes back directly to the atmosphere by evaporation, another part is absorbed by trees and plants ending up in the atmosphere by transpiration or to the ground through filtration along stem and roots, and the rest of the precipitation runs through the porous natural surface and infiltrates in the soil which eventually ended up in subsurface flow to the rivers or storage and percolates in the groundwater (Milligan, 2022). Figure 2.1.1 shows a comparison between natural and urban hydrological cycles to show how the volume of surface runoff changes due to impervious surfaces in urban areas. In the following figure natural setting stands for natural hydrological cycle.

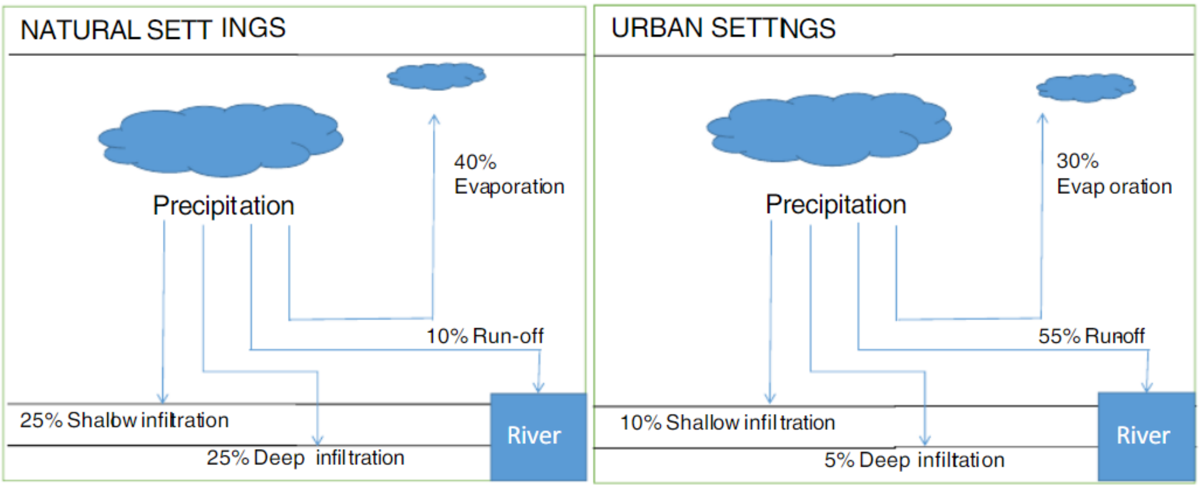


Figure 2.1.1: Change in the volume of surface runoff with changed hydrological cycle in urban areas due to increased impervious surface. (Source: (Saraswat et al., 2016))

A major part of precipitation (55%, see Figure 2.1.1) runs to the recipient water bodies in terms of runoff which is conveyed usually by a combined sewer or stormwater pipe network in a city. In urban areas due to changes in land use with high-rise buildings to ensure accommodation for the people, with huge impervious roads and pavements to facilitate traffic, the existence of several underground constructions and usages, and lack of sufficient green areas with trees and plants the hydrological cycle changes from the usual natural cycle (ibid). As a result, in urban areas, precipitation produces an enormous amount of runoff which is conveyed conventionally by the pipe network system throughout the city area exceeding the drainage capacity of the existing pipe network and resulting in pluvial flooding (ibid). A study on change in runoff due to urbanization and climate change impact in the U.S.A. found the runoff increased in terms of runoff rate, and peak discharge and resulted in a reduced time of concentration (Anne C Blair et al., 2011). The results found by the study are presented in the following figure for easy understanding.

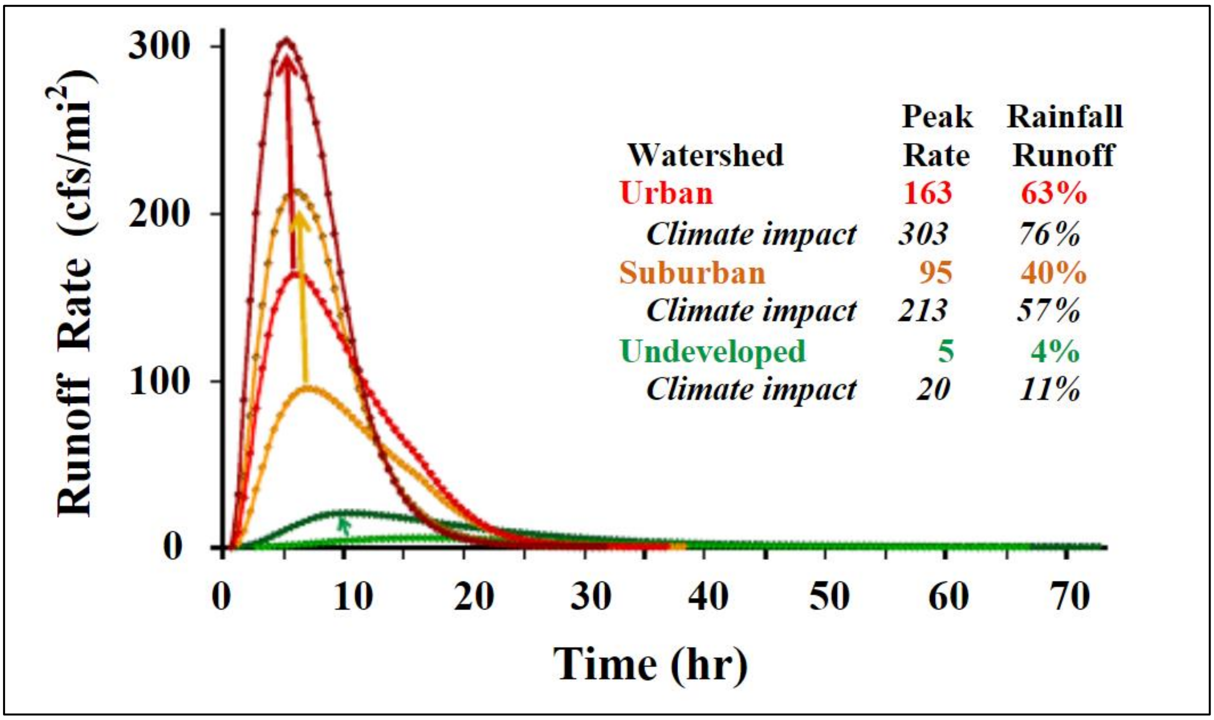


Figure 2.1.2: Graph illustrates the impact of urbanization and climate change on runoff volume, and climate impact is based on a 12--hour 5.175--inch storm, semi--saturated runoff conditions (source: (Anne C Blair et al., 2011)

The time water drops need to reach the receiver from its dropping point, called concentration time, is naturally high (US EPA, 2015b). Lack of sufficient amounts of other water cycle phases like evaporation, transpiration, infiltration, and the presence of impervious surfaces makes the concentration time short (ibid). Lag time which is the time needed to reach maximum flow in a catchment from the beginning of the precipitation also shortened (ibid).

It results in a sudden increase in load in the drainage system and overflows happen. D.G. Anderson pointed out that the lag time reduction along with an increase in stormwater runoff due to impervious surfaces can increase urban flood risk by two to eight times (*Effects of Urban Development on Floods in Northern Virginia*, 1970). (Feng et al., 2021) claimed urbanization increases the surface runoff and discharge but decreases the lag time. They also found spatial variation in land use worsened the situation. (Quan, 2021)'s study also found that urbanization or increasing impervious surface and change in land usage leads to an increase in surface runoff which increases the flood risk. Expansion of the modified environment due to urbanization implies extensive extraction of groundwater, underground construction, and modification of ground level, flow pathways, and steam slopes that escalate the vulnerability of urban pluvial flooding (Yin et al., 2015).

2.2 Impact of the Urban Drainage System on Pluvial Flood:

Conventionally closed pipe networks combined with or separated from sewer network systems are in use to quickly drain out runoff produced by precipitation in urban areas (Seyedashraf et al., 2021). Inadequate maintenance, aging of pipes, climate change impact including an increase in rainfall magnitude and frequency, population, and size of the city have an impact on the risk of basement flood in urban areas in Sweden (Okwori et al., 2020). Mixed usage of drainage systems is being practiced in Sweden, though separated sewer systems dominate. J. Sörensen's study found urban, or basement flooding is correlated with the intensity and spatial distribution of rainfall and the type of drainage system (Sörensen & Mobini, 2017). S. Mobini spotted that a combined sewer system is exposed to a higher risk of basement flood than a separated sewer system (Mobini, 2021). V. Nilsen claimed more frequent and severe overloading of existing sewer systems leading to urban flooding and higher discharges through combined sewer overflow (CSO) as the primary adverse effect of urban drainage systems (Nilsen et al., 2011). On the other hand, in recent eras a tendency to include more green spaces to enhance previous surfaces in urban areas is visible. A study by K. Berggren indicated the necessity of further study on pervious surfaces as it could contribute to urban runoff in a changed climate because of more frequent rainfall and extreme rainfall events (Berggren et al., 2013).

2.3 Climate change impact on Pluvial flooding:

Climate change will have a worse impact on urban flooding as rainfall intensity increases with climate change (Semadeni-Davies et al., 2008). A study on climate change impact in Europe claimed to experience an increase in intensity for extreme one-hour events all over Europe in general whereas the highest change will hit the Scandinavian region (Larsen et al., 2009). A 20-year 1-hour precipitation event will for example become a 4-year event in Sweden(ibid). This changed rainfall pattern would add extra stress on drainage flood management in the urban drainage systems which will raise the risk of urban flooding (ibid). H. Tabari claimed global warming would intensify extreme precipitation and flood events in all climate regions and increase precipitation and flood magnitude (Tabari, 2020). Climate change increases the frequency and intensity of extreme rainfall and flood hazards are also intended to increase with temperature rise (Blenkinsop et al., 2021). V. Nilsen conducted research on combined sewer systems in a changing climate and found CSO to increase in backwater levels in pipes and flooding in manholes which means more risk of basement flooding in urban areas with a changed climate for the period 2071-2100 (Nilsen et al., 2011). A potential propagation of surcharge and spilling volume will happen with climate change impact in the future and eventually, more claims of basement or urban flooding will happen (Abdellatif et al., 2015). Total spilling water volume from the flooding manholes can increase 2 to 4 times more than the increase in precipitation and total CSO can increase 1.5 to 3 times than precipitation *(Nie L et al. 2009).*

2.4 Sustainable stormwater management:

Concept of Sustainable Drainage System

Sustainable stormwater management uses different LID practices to mimic the natural hydrological cycle in urban areas which mainly aims to reduce runoff, increase infiltration, and other components of the hydrological cycle resulting in decreasing flood risk and erosion downstream and improving the water quality (US EPA, 2015a). On the other hand, conventional practice for urban drainage included a pipe network and some underground basins to convey the stormwater along with or separated from the sewer water system to the recipient water body to keep the urban area well drained. The design was used to be done based on maximum discharge, and frictional loss of pipe materials (Siddha & Sahu, 2022). There was not much provision for water quality and other benefits they could offer (ibid). In conventional urban drainage systems, the design mostly focused on water quantity, and treatment plants were used for quality control but very little attention to amenities and biodiversity (*Sustainable Drainage*, 2023). But in SUDS the design is based on a combination of water quantity, quality, amenities, and biodiversity (ibid). Figures 2.4.1a and 2.4.1b present the difference between conventional and sustainable drainage systems' concepts.

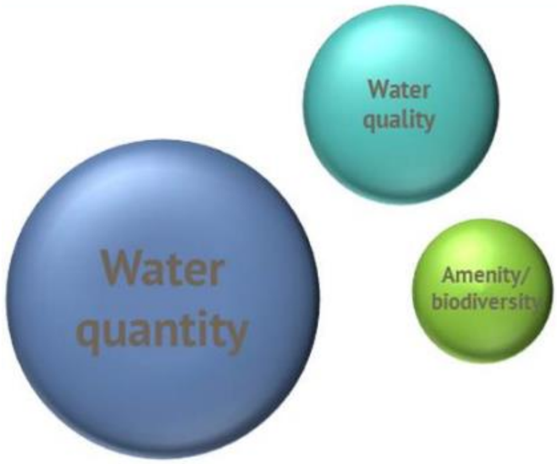


*Figure 2.4.1a: The conventional urban drainage system where water quantity was mainly focused, and different services were used to take care of water quality, amenities, and biodiversity on a small scale. Photo:(*Sustainable Drainage*, 2023)*

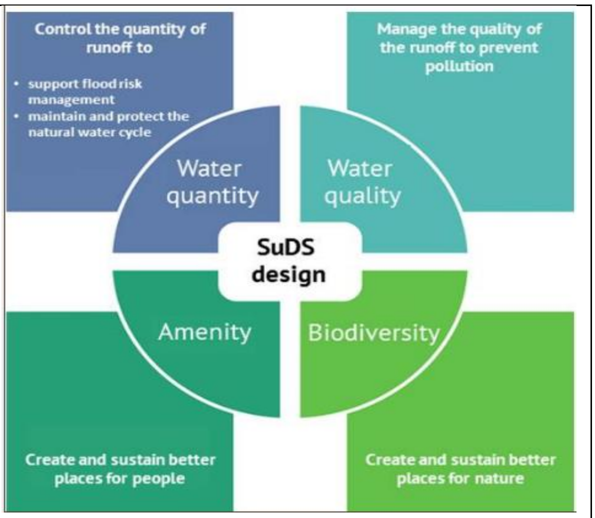


*Figure 2.4.1b: The SUDS design concept where water quantity, quality, amenities, and biodiversity of all four services are combined. Photo:(*Sustainable Drainage*, 2023)*

European flood risk directive suggested a 3P formula for flood risk management which is (1) not to build cities in flood-prone or adapt to future flood risk(prevention), (2) restoring wetlands and flood plains as measures to reduce flood risk (protection) and (3) public awareness about to survive the flood (preparedness) (RECONECT [@H2020RECONECT], 2019). A Sustainable urban drainage system is a departure from the conventional meaning of management to convey water with pipelines and replaced with a system to mimic the natural hydrological cycle that can retain and detain water, reduce surface runoff, increase infiltration, introduce green areas leading to more evaporation, and transpiration along with pollutant reduction (Tang et al., 2021). LID practices help maintain natural hydrologic cycles through site grading, vegetation, soils, and natural processes that absorb and filter stormwater onsite (ibid). SUD principles mimic the natural hydrologic cycle and take a holistic approach to stormwater management with an interdisciplinary team (*SuDS Principles*, 2023).

In a sustainable urban drainage system, it is flexible to choose from different components from varieties depending on their techniques and purposes. Components can be categorized as source control, onsite controls, slow transports, and downstream control (Sörensen, 2018). Figure 2.4.2 illustrates these different categories. Facilities like green roofs, rain barrels on private

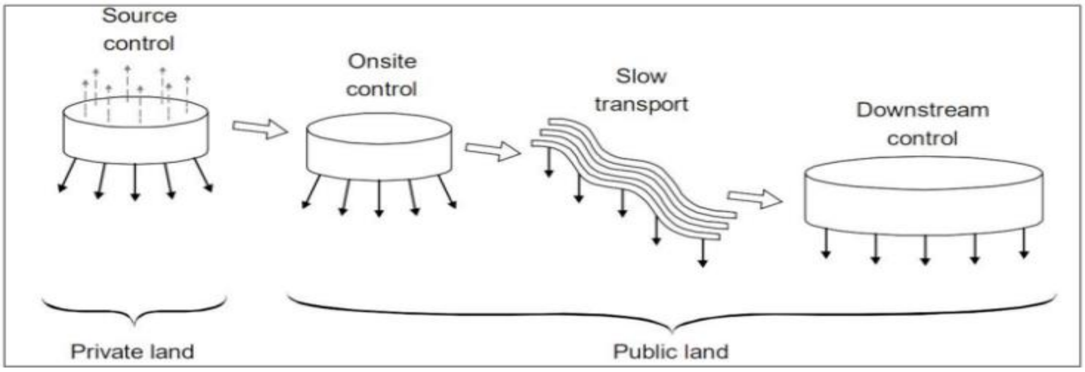


Figure 2.4.2: Techniques used in SUDS. Source: (Sörensen, 2018)

land etc. can work as source control and pervious pavement, rain gardens, bioretention cells, magazines, retention or detention ponds, wetlands, etc. can work as onsite controls, channels, swales, etc. can be used to slow down the transportation process and increasing lag time. Large retention ponds, wetlands, lakes, etc. lying downstream of the water management train are known as downstream control (ibid). Considering the spatial variation of rainfall in the catchment and choosing the components depending on the locations, roles, and functions in the system and the location and source of the flood risk are important to planning, designing, and executing SUDS components (Seyedashraf et al., 2021). These are also known as LID, BMP, and Blue-green solutions though there can be differences in performance and functions (Seyedashraf et al., 2021). Bio retention cells can give optimum benefit to reduce runoff peak regardless of the slope of the surface, whereas pervious pavement can perform best for lower or average slopes, and rain garden or bioretention cell can provide the best solution for pollutant reduction (ibid)

S. Sarkar found in their study blue-green infrastructure is a potential solution to mitigate flood risk with most of the projected climate change impacts (Sarkar et al., 2018). A study on conventional pipe network systems and open stormwater systems (OSWS) by A. Shukri found a longer lag time and about a 50% reduction in discharge with OSWS than with pipe networks (Shukri, 2010). They found less severe flooding with OSWS. Another study claimed Blue-Green-Gray as a system for future uncertain climate change and land usage (Green et al., 2021). Urbanization and projected increase in precipitation due to climate variabilities and change will worsen the current urban flooding and combined drainage problem alone or together (Semadeni-Davies et al., 2008). Implementation of a sustainable urban drainage system (SUDS) will reduce the adverse effect of urbanization and climate change i.e., urban flooding along with a positive effect on the urban environment (ibid).

A study by (Haghighatafshar et al., 2018) found that to enhance flood mitigation, catchment isolation is a key aspect. His study suggested retrofitting a blue-green stormwater system to control local pluvial floods in urban areas as it can reduce the inundated surface by almost 70%, the peak flow from a cloudburst by 80%, and level out the runoff. They said retrofitting BG to implement primarily in upstream areas of a pipe-bound catchment to benefit the entire downstream network as a basement could still be a problem with retrofitted BG systems depending on the magnitude of discharge coming from the upstream network. Sustainable drainage systems were also found to be cost-effective for construction, operation, and maintenance compared to conventional pipe network systems (Duffy et al., 2008)

The concept of Bluegreengrey (BGG)

Kabisch et al., 2017 describe Blue -green-gray as a hybrid system of ecosystem services (water and green spaces) blue-green, and the engineered parts of an urban area (buildings, pipe networks, or other concrete structure that has longer life span) as gray infrastructure. They also referred to blue-green ecosystem services as a tool for multiple hazards, flooding, temperature, and erosion control(ibid). L. A Wendling suggested Blue-green-gray as a holistic sustainable urban water management system that connects urban waterways, green spaces, and gray infrastructure and enhances resilience to climate change for urban areas (Wendling & Holt, 2020). Another study mentioned Blue-Green-Gray as a system to boost natural and ecosystem service along with flood mitigation where the researchers mentioned existing pipe network systems as grey infrastructure. (Ncube & Arthur, 2021)

The concept of BGG introduced by Edge is a solution that combines the above-described blue, green, and gray services to function as one while providing all the above three services and it is written as bluegreengrey. The principle used for BGG is almost the same as practicing blue-green-gray but here the gray service is used to define the roads or pavement structures which has traffic load-bearing capacity and are present in the urban areas causing imperviousness but modified with higher porosity to store water in its open subbase layer. More details are described in the next paragraph. Edge describes BGG as a system that cleans and retains stormwater simultaneously with support for green spaces in cities and allows flexible design for roads ensuring traffic loads (*Livable-Streets-A-Handbook-of-Bluegreengrey-Systems-Version-2.0.Pdf*, 2020). It helps lower the urban streets' temperature which minimizes energy consumption and improves groundwater recharge while fulfilling the load bearing and traffic load requirements. (ibid).

The uniqueness of Edges introduced BGG is that it doesn't need separate space for stormwater retention or detention rather uses the modified subbase layer of existing roads and parking spaces to function and simultaneously store and purify stormwater and provide it for vegetation, trees, and green spaces in urban area which doesn't need a separate space for the root zone. They introduce an Open subbase layer (OSL) that can replace the conventional subbase layer under pavements to create space for retaining or detaining stormwater, It also uses the same space to provide scope for green spaces or trees in roads and finally, it is capable of necessary load bearing for the specific traffic. Figures 2.4.3 and 2.4.4 can illustrate this concept more clearly. In OSL macadam or coarsely crushed.

*Figure 2.4.3: The concept of the BGG system introduced by EDGES where the crucial infrastructure of a city i.e., roads are included in stormwater management in urban areas. The sub-base layer is replaced with an open subbase layer (OSL) to make rum for retaining water and accommodate bioretention areas or tree trenches together while providing a hard surface on the top to carry traffic loads. In this BGG OSL section is continuous along the long section of the street to maximize the capacity (*Livable-Streets-A-Handbook-of-Bluegreengrey-Systems-Version-2.0.Pdf*, 2020)*

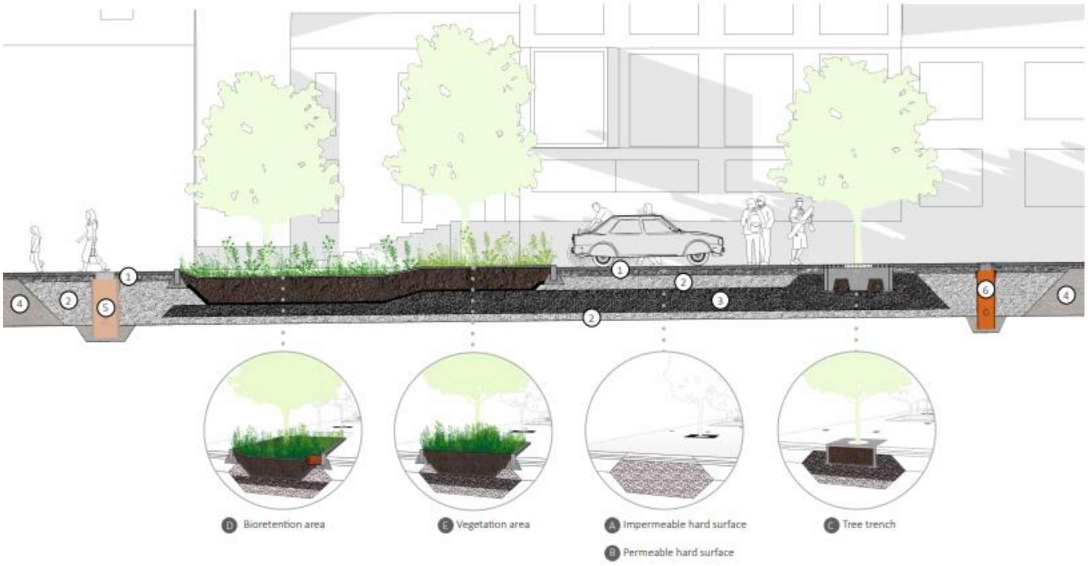


*Figure 2.4.4: Long section of a street with BGG system showing how the OSL interconnect water space, green vegetation, or tree spaces along with grey structure or streets(*Livable-Streets-A-Handbook-of-Bluegreengrey-Systems-Version-2.0.Pdf*, 2020)*

stones are being used to ensure open space for water. The sieve size of the materials used in OSL depends on the purpose like retention, bioretention, and load bearing. Biochar and compost are mixed and replaced in OSL to retain water and nutrients to provide healthy trees or green spaces. This layer also binds nutrients and other pollutants from surface runoff and purifies the water to enhance water quality. Retention of water in OSL also enhances the percolation of water into natural subgrade surface i.e., groundwater percolation, and mimics the natural hydrological cycle. Stormwater can be sent to the OSL through pervious pavement or pits but in the end, microorganisms, and plant roots in the OSL break down the pollutants and effectively purify water when these function as nutrients for plants. It means the BGG system includes roads and/or parking lots to retain stormwater, ensure nutrients, and store water for healthier trees and plantations in urban areas. It is possible to build BGG even on surfaces with higher slopes in a stand-alone way instead of the long stripes shown in Figure 2.4.3. Figure 2.4.5 and 2.4.6 shows an implementation of BGG in parking and stand-alone way.

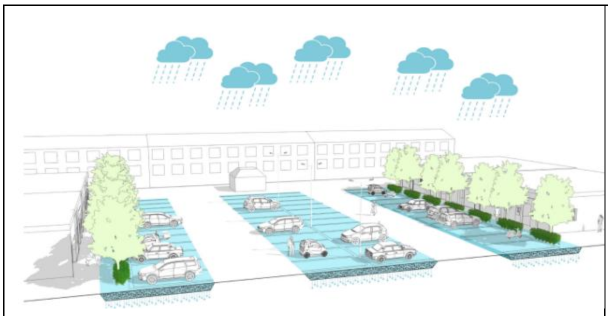
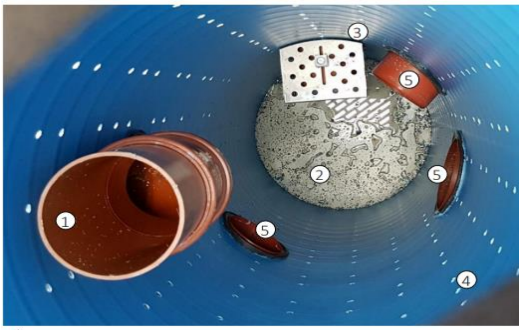


*Figure 2.4.5: BGG in parking lot (*Livable-Streets-A-Handbook-of-Bluegreengrey-Systems-Version-2.0.Pdf*, 2020)*

*Figure 2.4.6: BGG in the steeper surface in a stand-alone way (*Livable-Streets-A-Handbook-of-Bluegreengrey-Systems-Version-2.0.Pdf*, 2020)*

Stormwater follows low lines to reach low points and then can be led to a subbase layer via a control pit, permeable surfaces, or bioretention areas. Control pits are used to lead the stormwater either in the subbase layer BGG cell unit or the drainage pipe. Figure 2.4.7 shows a control pit and its components. A control pit is a perforated stormwater chamber or pipe that has an overflow pipe at the top to lead excess water directly to the conventional drainage pipe in case of heavy rain. Adjustment of this overflow pipe depends on the function of the BGG system. If it is designed to manage extreme rain, stormwater is first directed to the sewer pipe and led to the subbase layer only during the flood. In this case, the sewer pipe or stormwater pipe determines the design flow from the catchment. In the case of managing dimensioned rain stormwater led to the subbase layer first and then to the pipe network when the subbase layer reaches its storage capacity. Here the flow regulator or overflow controls the flow from the catchment. When BGG units are connected, flow regulators are used to bypass stormwater excess to the storage capacity of the open subbase layer, and stormwater is retained in the open subbase layer for a longer time, it is expected to get a higher degree of purification and availability of water for vegetation. How the stormwater passes through the bioretention area, infiltrates, and retains in the open subbase layer, and drains out via an overflow regulator during different types of rain (light, moderate, and heavy) with a BGG unit are illustrated in the following figures from Figure 2.4.8 to Figure 2.4.10.



Control pit from above.
1. Overflow pipe
2. Sand trap
3. Flow regulator with protective cage
4. Perforation for percolation and discharge
5. Pipes for dispersion, discharge and roof runoff

*Figure 2.4.7: Control pit and its components (*Livable-Streets-A-Handbook-of-Bluegreengrey-Systems-Version-2.0.Pdf*, 2020)*

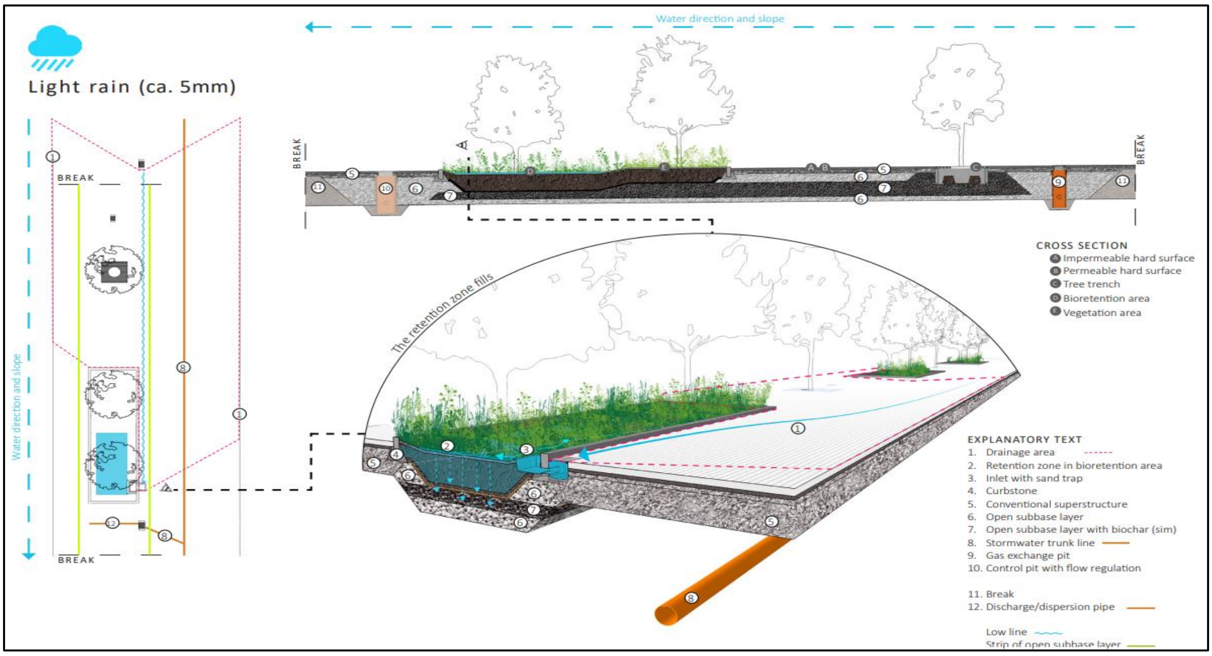


*Figure 2.4.8: In case of light rain stormwater follows the low line and enters the bioretention layer of BGG.(*Livable-Streets-A-Handbook-of-Bluegreengrey-Systems-Version-2.0.Pdf*, 2020)*

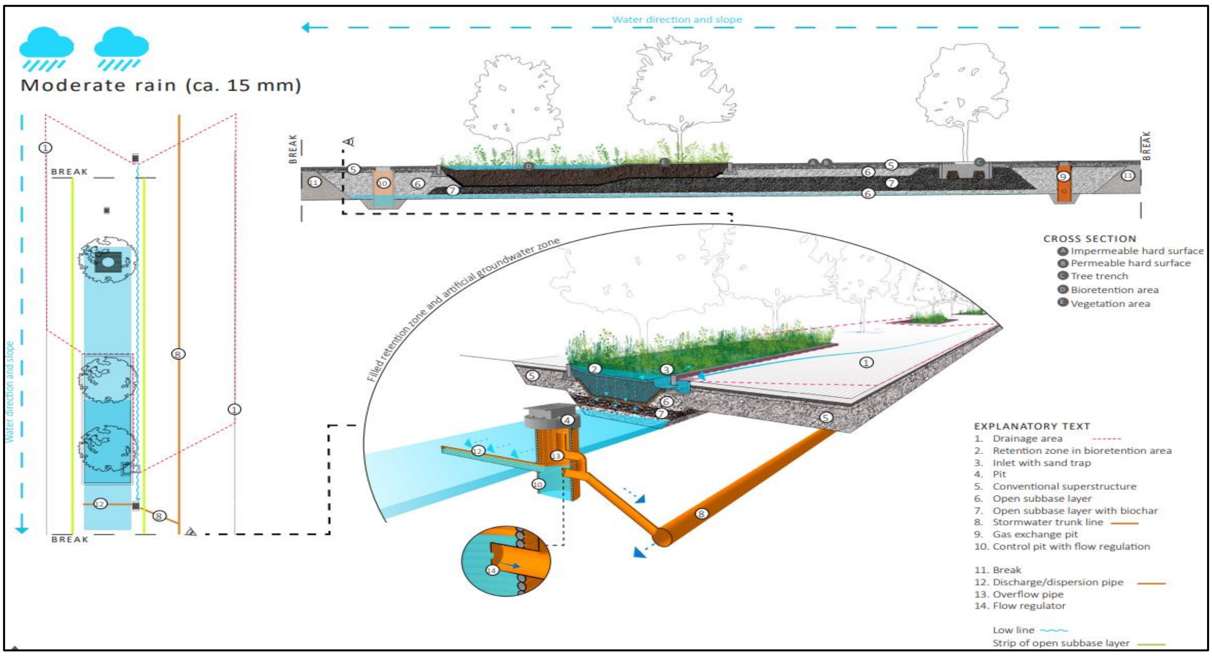


Figure 2.4.9: During moderate rain, stormwater is filtered into the open subbase layer through the bioretention layer. This retained stormwater can be stored for a longer time in an open subbase layer or bypass the conventional pipe network with a flow regulator. (ibid)

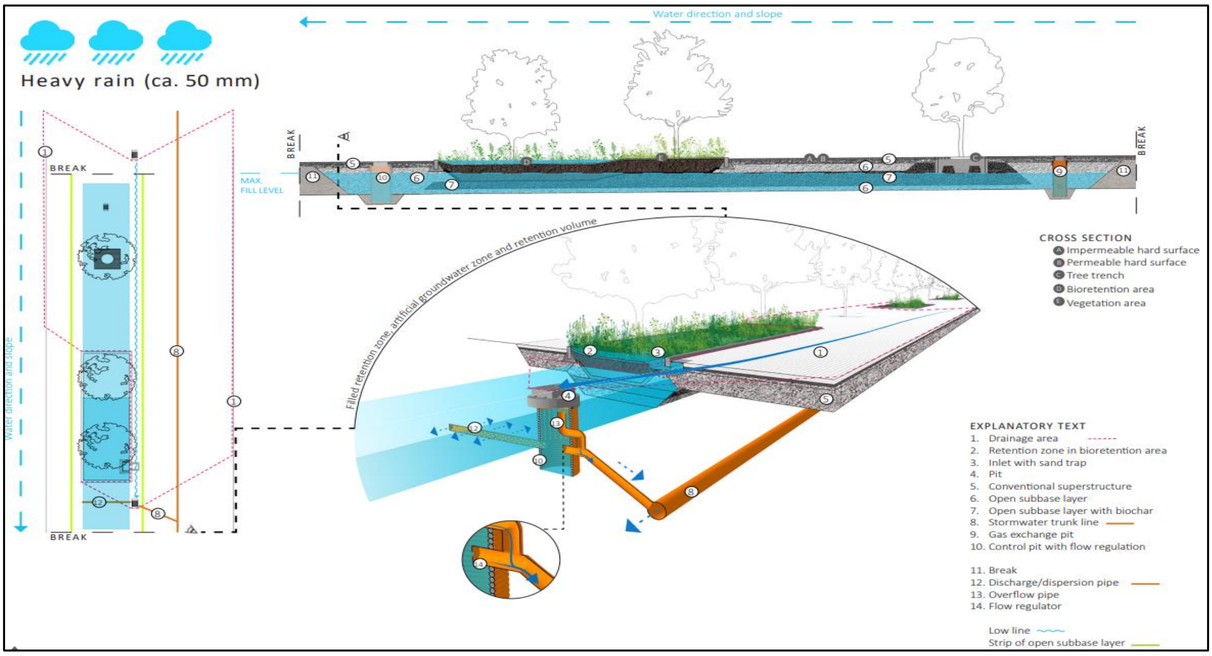


Figure 2.4.10: During heavy rainfall when the open subbase layer is full to its capacity the excess water can be led to a conventional pipe network with a pit or overflow pipe. (ibid)

After heavy rainfall when the open subbase layer is full of its capacity the retained stormwater is bypassed to the pipe network with the pit and the flow regulator via the overflow pipe. Usually, it is done within 24 hours after the storm. This function is used to empty the open subbase layer for repair and maintenance. Here the retained stormwater can be fully bypassed to the pipe network to empty the subbase layer or the excess water can be bypassed, and the retained stormwater can be allowed to stay longer to ensure availability for the vegetation and the greater extent of purification.

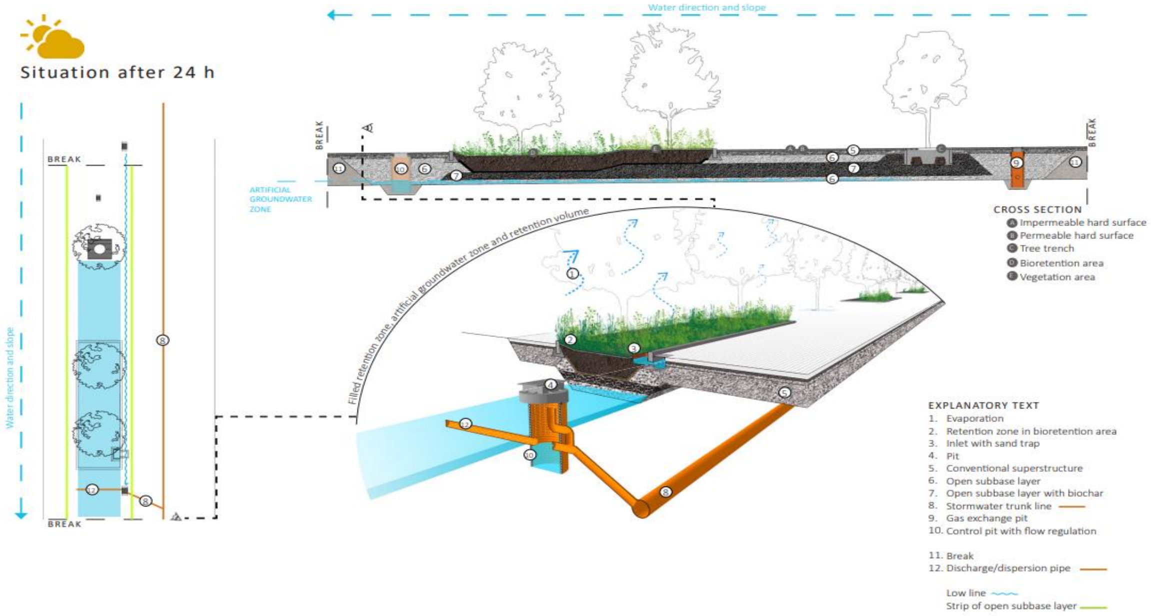


Figure 2.4.11: A BGG unit and open subbase layer after a storm when the excess stormwater is bypassed to the pipe network with the flow regulator. (ibid).

In the BGG system, its key components such as permeable or impermeable hard surfaces, tree trenches, bioretention area, vegetation area, and open subbase layer are interconnected to integrate blue, green, and grey parts of an urban area. Instead of a single purpose of different components they are interconnected and built together to function as one integrated multifunctional element. The BGG expert K. Fridell claimed BGG can reduce the demand for space to about half of that required by the same components when they are not interconnected through OSL.

Biochar which is used to construct an open subbase layer in BGG works as a carbon sink for the city and can store about 135–300-ton CO_2e/ha (*Livable-Streets-A-Handbook-of-Bluegreengrey-Systems-Version-2.0.Pdf*, 2020). The vegetation and control pits used in BGG can delay and regulate the water flow to result in 5-30 l/s/ha of stormwater even with a 1.25 climate factor whereas a 10-year rainfall with a 10-minute duration can produce a stormwater flow of around 250 l/s/ha from streets without BGG (ibid). A conventional sewer system is usually designed for 2-10 years of rainfall without any retention capacity, but a BGG system is usually designed for 30 years of rainfall with a 1.25 climate factor (ibid). Though the purification measure is still under study, a BGG is expected to purify stormwater 70-80%.

2.5 Site Introduction:

The purpose of this report is to investigate if the implementation of BGG can be effective in reducing the extra stress in the existing pipe systems for the combined sewer system and if it can make the pipe system functional for a 10-year rainfall event. Though most of the existing combined sewer systems in Sweden were built a long time ago, municipalities have a responsibility to make this existing network functional for 10-year rain today (Mobini et al., 2020). A district in the upstream area of Trelleborg city is mostly occupied with residential buildings, villas, streets, and roads which are mainly used by low to medium-traffic loads. Though this area has good green spaces, a lot of impervious streets are producing a large amount of runoff while the existing pipe network goes under stress during heavy rain and causes basement flooding which was reported quite frequently.

Most of the houses are occupied with green space and pervious parking lots. A small playground and a school lie in the study area. This area doesn’t receive any discharge from the upstream network as it lies upstream of the network itself. A stormwater collection system was built later with separate stormwater collection pipes to collect runoff from one street on the west side of the study area to reduce the discharge in the combined pipe network. Pedestrian Lanes, bike lanes, parking grounds, along tree trenches big trees lie in the study area where BGG can be installed in various forms as described in the theoretical background. Figure 2.5.1 introduces the study area along with features and the location of households having basement flooding issues.

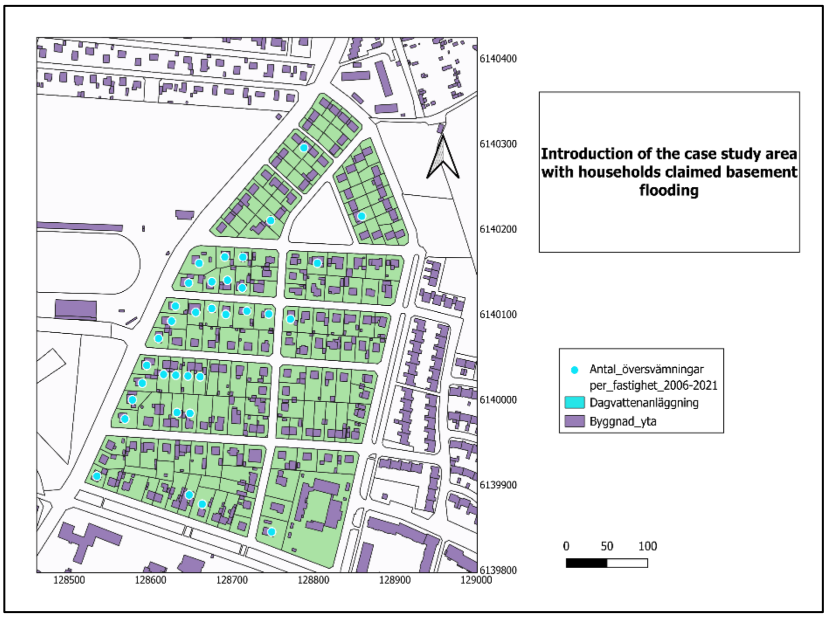


Figure 2.5.1: The case study area of Trelleborg city with existing features and households having basement flooding.

2.6 Mike+

Mike+ is a modeling software introduced by DHI to understand, simulate, analyze, and craft resilient water systems. This can be used for the holistic management of water resources to support strategies with driven data. This software can be helpful for engineers and decision-makers to simulate runoff from rainfall as hydraulic loads in the pipe networks, test several sustainable design options to minimize the flood risk, and find cost-effective potential solutions. It provides the opportunity to simulate the real scenery, predict the changes, and make necessary future measures to make a more resilient water system considering future urbanization and climate impact.

Hydrological models are simplified and conceptual representations of components of the hydrological cycle which can be used for the purposes described above. The underlying basic concept of a hydrological model is the continuity balance of water i.e.

Total rainfall inflow (volume) = Losses(volume) + Runoff (volume) + Storage (volume)

Mike+ considers infiltration and evaporation as losses. Mike+ can be used for features like catchments, collection system networks, river networks, and 2D overland flow with modules rainfall-runoff (RR), Hydrodynamic (HD), Transport, water quality, sediment transport, and data simulation. Mike+ is facilitated with several tools and computational models for hydrological modeling. Mike+ provides four surface runoff models (Time-Area method, Kinematic wave, Linear reservoir, Unit hydrograph method) for runoff modeling. Kinematic wave models can be used to install and test the performance of different sustainable design elements. Calibration and verification of the model are important to justify the model simulation, response, or results and fit to reality. Modeling of urban rainfall-runoff, infiltration, and process used by Mike+ can be illustrated by the following figure 2.6.1.

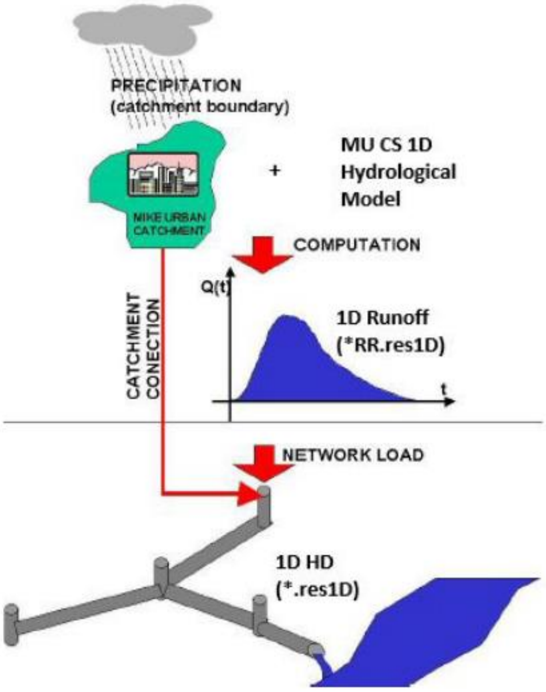


Figure 2.6.1: Representation of hydrological modeling including rainfall runoff and collection system with Mike+ (source: MIKE+ collection system guideline)

To compute the load from rainfall (stormwater load) in the pipe network system runoff modeling uses catchment, connection points (nodes) to the network system, and precipitation under various boundary conditions for different scenarios. In this study, Kinematic wave (model B) has been used to simulate precipitation, runoff, and loads in the collection system (existing pipe network) and use and test the performance of some LID designs to test efficiency to reduce runoff i.e., the load in the network system. How Mike+ compute the load and the result is used in forecasting flooding in pipe system (basement flooding) are discussed thoroughly in the methodology section later.

3. Methodology and Materials of the study:

3.1 Methods

Mike+ can do a hydrodynamic simulation of flows and water levels in the pipe network system for stormwater drainage and/or wastewater collection which can give a clear knowledge about how the network will function under a variety of boundary conditions. Hydrodynamic modeling for the network in Mike+ consists of defining the network, specifying the boundary conditions, adjusting computational parameters and simulation of the reality, and finally result from analysis.

A hydrodynamic model consists of several hydraulic elements like nodes and structures, pipes and canals, weirs, orifices, pumps, valves, etc. Nodes represent the manholes and pipes and canals represent the connecting pipes in this model. In pipes and canals, the computational grid is set up to calculate h (water level) and Q (discharge) in an alternate sequence for each time step where h is always at the connecting or ending points i.e., nodes. The nodes have only a single computational point to compute only the water level h. Figure 3.1.1 below illustrates the computational grids in connecting pipes canals and nodes.

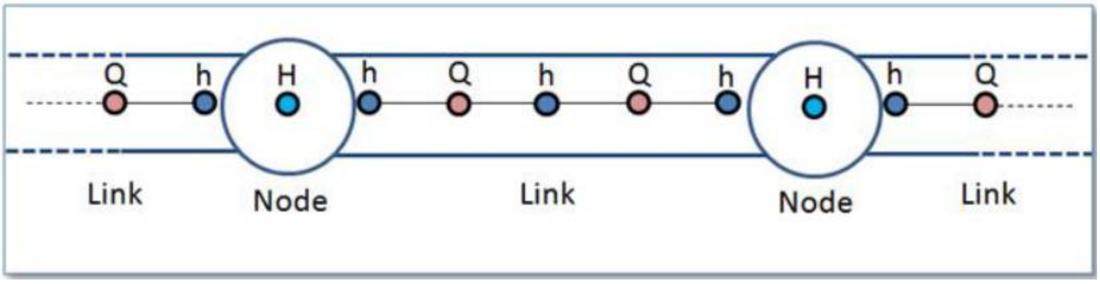


Figure 3.1.1: Computational grids in nodes and connecting pipes and canals.

Thus Mike+ can be used to compute the water level at nodes to predict the basement flood but not the discharge or flow data at nodes. Depending on the provided geometry the storage volume of water in the nodes is calculated. At nodes, the water level is evaluated from the water level at the previous time step and flow contribution from each connected pipe and externally connected flow from catchment runoff discharge for the time step.

The water level at time t1 = water level at time 0 (t0) + storage by time step dt.

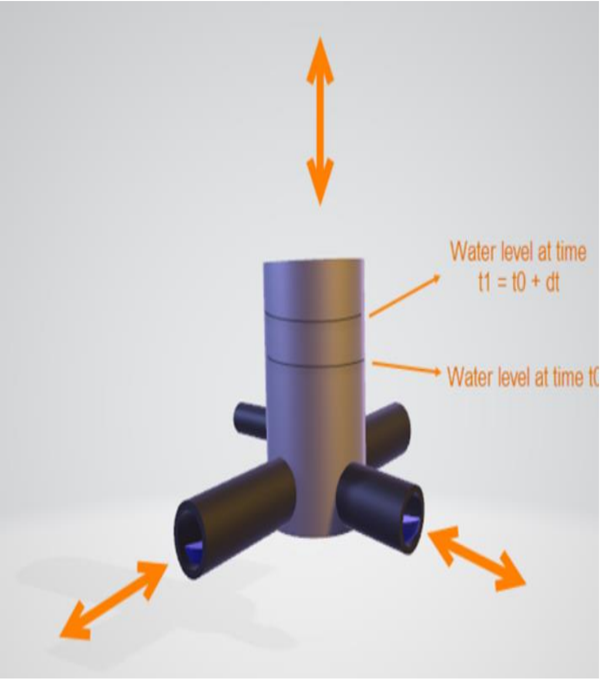


Figure 3.1.1: computation of water level from flow in nodes. Source: Mike+ guideline

Figure 3.1.1 illustrates the mechanism for better understanding. Sustainable urban drainage structures are used in terms of LID (low impact development) in Mike+ where the principle is to mimic natural landscape features or natural hydrology by minimizing the effective imperviousness and creating a drainage system where stormwater can be treated as a resource instead of a burden. The modeling of LID elements has two approaches, one is the catchment-based approach at the screening level and another one at the drainage network based on detailed hydraulic modeling of each LID structure. The first approach gives the volume of water in different phases like runoff, infiltration, storage, and loss in each catchment where the LID structure is deployed. The numbers of LID structures, and parameters and size of LID structures are possible to define by the user to assess the ability of different types of LID structures to reduce the runoff in catchment level and the load in terms of water level in the pipe network system. Implementation and asses of LID structures by Mike+ are only possible with the Kinematic Wave runoff model (Model B) and they are conceptual elements it is not possible to visualize them in the model. LID structures are considered as the properties of the catchment they are deployed in. Mike+ has provision for seven types of LIDs named bioretention cells, infiltration trenches, porous pavement, rain barrels, vegetative swales, rain gardens, and green roofs. In this study, bioretention cells and porous pavements are used to simulate BGG and to assess their capability to reduce basement flooding. Why they were chosen for this study and their parameters are described in a later section.

3.2 Model Setup and Calibration

The base model and its setup are provided by DHI. The model is divided into 52 catchments along with 54 nodes. 52 Nos of them are manholes to connect the pipe network with the catchment. One manhole and 1 outlet are out of the catchments to measure the outflow from the total study area. Catchments were set by the time-area method and the imperviousness of the catchments was calculated from roads, buildings, and other built-up areas with impervious surfaces. Different reduction factors were used in different catchments to calibrate the model. Surface runoff and discharge were calculated only for impervious surfaces as in model B only impervious surface contributes to runoff.

A calibrated model was received from DHI via the model supervisor to study the case study area with different setups, boundary conditions, and scenarios. The calibration was done with measured data at three nodes in the model named ANB8, ANB17, and ANB 115. Among them, the first two are laid on Road A near flood-affected households and the last one is out of the catchment setup of the study area which gives measurement for the outflow data from the study area. A separate stormwater network was constructed in Road A and the stormwater from that part is directly conveyed by that stormwater collection system and bypassed out of the case study area. The influence of this separate stormwater system was fitted in the model by several boundary conditions to calibrate the model. The details of the model calibration are not included in this study and can be found in DHI officials. Figure 3.2.1 and 3.2.2 shows the layout of the existing separate stormwater network and the nodes used to calibrate the model.

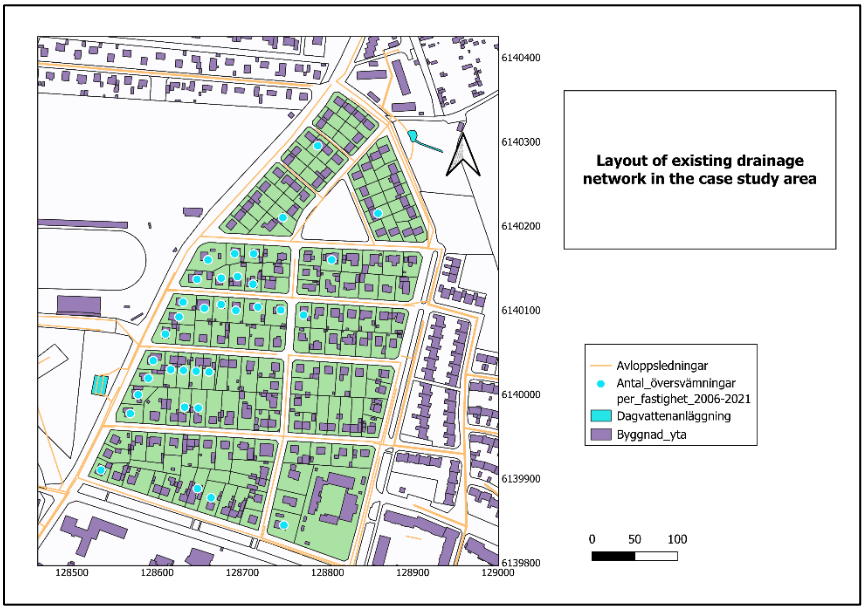


Figure 3.2.1: Study area in Trelleborg municipality showing roads, constructed areas, and combined and separate stormwater pipe network system.

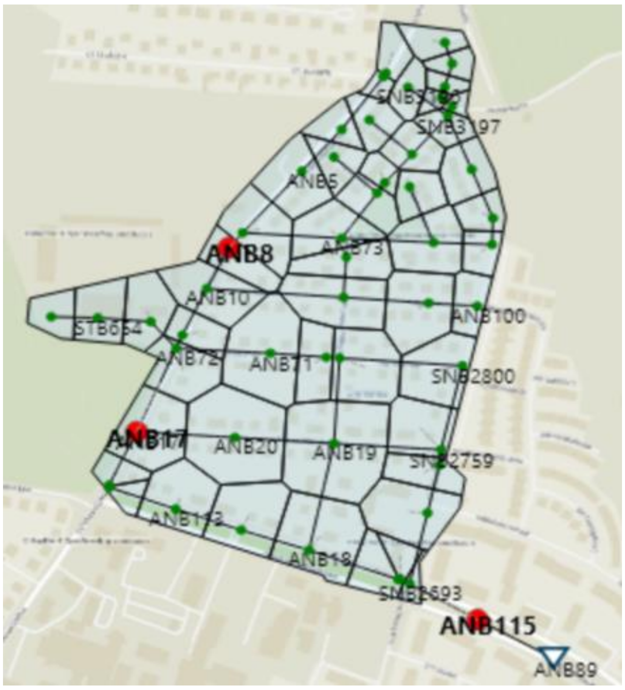


Figure 3.2.2: Model setup with Nodes and the measured nodes used to calibrate the study area.

3.3 Model set up with BGG.

One of the main purposes of this assessment was to reduce the surface runoff from the catchments to reduce the load in the pipe network. A study by (Wang et al., 2019) suggested that the bioretention cells and porous pavements could have a significant influence to reduce the surface runoff and peak discharge for short return period rainfall events. There is no specific LID structure option available in Mike+ named BGG.

In the BGG system the open sub-base layer of an existing road is used as a storage layer to retain or store stormwater, The substrate layer and the portion of the open subbase layer with biochar are used as the soil layer to provide room for root zone and nutrients for trees and plants, and top surface with vegetation cover and soil grains with high porosity are used to receive stormwater and bypass it to the open subbase layer. In this model, Bioretention cells were used to simulate BGG with modified parameters. In Mike+ the bioretention cell units have provisions to use a storage layer, soil layer, and top surface layer like the function of a BGG unit.

Figures 3.3.1 and 3.3.2 illustrate the simulation of BGG by bioretention cells.

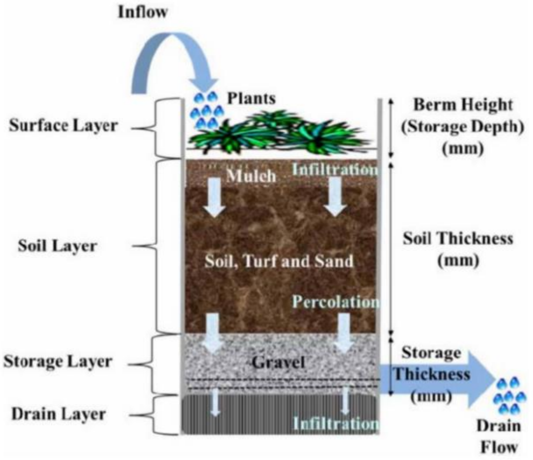


Figure 3.3.1: Components of bioretention cell. Source: (Gülbaz & Kazezyılmaz-Alhan, 2017)

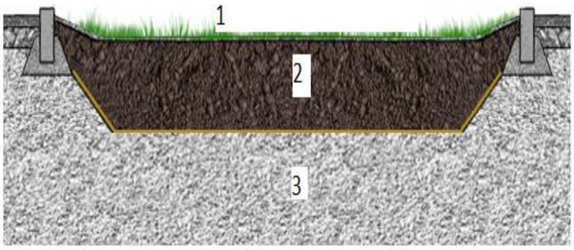


*Figure 3.3.2: Cross-section of BGG to compare with bioretention cells. Source: (*Livable-Streets-A-Handbook-of-Bluegreengrey-Systems-Version-2.0.Pdf*, n.d.)*
1. Surface layer 2. Substrate layer equivalent to soil layer (replaceable with open subbase layer with biochar, 3. Open subbase layer equivalent to storage layer of bioretention cell.

According to the practicing parameters and depths of different layers of a BGG unit given by EDGEs are used to modify the layers of bioretention cells in the model and are described in the following table 3.3.1:

Table 3.3.1: Depth and parameters of different layers in Bioretention cells to simulate the function of BGG structures.

Layer	Depth (mm)	Vegetative Cover (%)	Porosity (%)	Infiltration rate (mm/hour)	Conductivity (mm/h)
Surface Layer	150	20%			
Soil layer	600	Not applicable	45	35	
Storage layer	300	Not applicable	33		10000

The vegetative cover percentage was to be set at a maximum of 20% to get an optimum reduction of runoff along with an aesthetic green view in urban areas. The surface slope was set to 5% as the maximum surface slope was not more than 5% in any catchment which was calculated from contour lines over the study area. The clogging factor was set to 0 at the storage layer as this layer doesn't have to clog in real-life practice for BGG.

It has already been described before that the BGG system can use the porous pavement at the top surface to receive stormwater and lead it downward in the open subbase layer. In Mike+ the LID option porous pavement has three layers surface layer, pavement layer, and storage layer. Porous pavements have similar hydraulic functionality as that of bioretention cells and the difference is that porous pavement surface (vegetation) and soil layer are replaced with porous concrete or asphalt. A conceptual diagram of porous pavement is illustrated in Figure 3.3.3 and parameters and depths are illustrated in Table 3.3.2 below. The parameters and depths of different layers for porous pavement cells were also modified according to the practicing depth, porosity, and infiltration rate of BGG structures. In porous pavement, the storage layer is allowed to infiltrate the retained or stored stormwater into the surrounding native soils depending on the value of conductivity. Hence the storage layer of the porous pavement unit was set with conductivity 0 mm/hour to prevent infiltration to the native soil and allow to mimic the storage capacity as that of BGG structures.

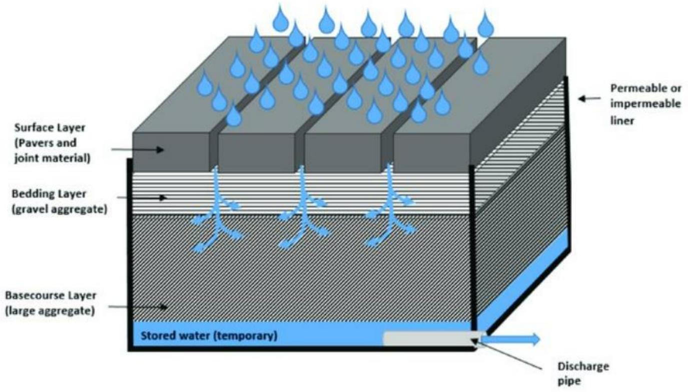


Figure 3.3.3:Conceptual diagram of Porous Pavement Structure (Hill & Beecham, 2018)

Table 3.3.2: Parameters set up for porous pavement to simulate BGG structures.

Surface layer	Depth: 0 mm ((Permeable Pavements: TTT - LID SWM Planning and Design Guide, n.d.) Vegetative Cover: 0 Surface roughness expressed by Manning's M value 83 (Mike+ guideline) Surface slope: 5% (as per slope of catchments according to contour lines map of the study area)
Pavement Layer	Depth: 200mm (Minnesota Pollution Control Agency, 2022) Porosity: 30% (Minnesota Pollution Control Agency, 2022) Permeability: 1000 mm/hour (PermeablePavement1008TechNote) Impervious surface: 0 for continuous porous pavement system Clogging factor: 0 as the permeability is already considered half of its initial condition
Storage layer	Depth: 600 mm to mimic the storage depth of the BGG system Porosity: 40% (Minnesota Pollution Control Agency, 2022) Conductivity: 0 mm/hour to prevent infiltration from the storage layer to the surrounding native soil layer.

The function of the flow regulator and overflow pipe in a BGG unit is simulated by the drainage function of the storage layer in the bioretention cell and porous pavement units. The offset height in the drain parameter in the model represents the height of the under-drainage pipe above the bottom of the storage layer. This offset height was set to equivalent to the depth of the storage layer of bioretention cells and porous pavement units to allow them to store or retain stormwater and bypass the excess water after reaching the capacity of the storage layer. This setup was designed to allow the retained stormwater to stay in the open subbase layer for a longer time so that it can be purified to a greater extent and be available for vegetation. The following sketch in Figure 3.3.4 can visualize this function.

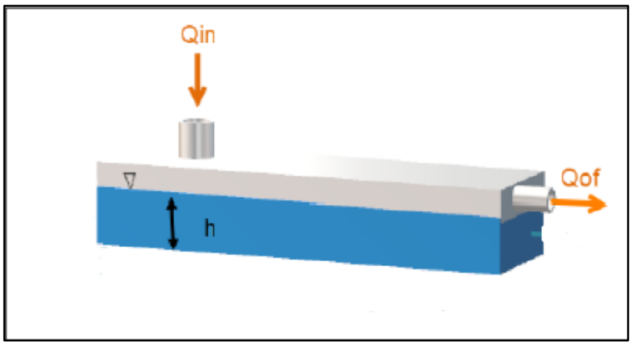


Figure 3.3.4: A conceptual sketch of how the function of the flow regulator and overflow pipe was simulated in the model.

3.4 Sizing and deployment of BGG structures in the study area

BGG in terms of Bioretention cells and porous pavements with modified parameters were placed along several roads in the study area. The length, the number of cells, and the surface area for each structure were determined depending on the road width, the necessary area for the plant roots, and the amount of impervious surface area in each catchment. The criteria were that the total area of collection by deployed cells (bioretention cell and pervious pavement) could not be more than the total impervious area of the catchment they belong to. Porous pavements were installed to be continuous along the roads and bioretention cells were deployed along the tree trenches not allowing a change in the existing landscape and bike and pedestrian lanes and allowing sufficient driveway for the house owners adjacent to the implemented area. Figures 3.4.1 and 3.4.2 show where these two types of BGG are suggested to be implemented.


[redacted]

Figure 3.4.1: A landscape where bioretention cells were placed. (Taken from Google map)


[redacted]

Figure 3.4.2: A landscape where porous pavements were placed (taken from Google map)

These two types of available LID structures were used to simulate BGG structures continuously along the roads and the standalone type of installation described in the theoretical background. Porous pavements were used to simulate BGG structures where they do not have vegetation cover, but porous pavement and the storage layer are connected to the tree root zone by pits to store and supply water for the healthy life of trees. Figure 3.4.1 shows the installation of bioretention cells and porous pavements in the study area to test their functionality and capacity to reduce the runoff and the load in the existing pipe network. Figure 3.4.2 presents catchment distribution among the case study area. The location of the proposed LID structures is representative as only their geometric and functional parameters are relevant to their performance. Roads are represented in the figure with the name roads A, B, C, D, E, F, G, and L to follow the confidential agreement with Trelleborg municipality.

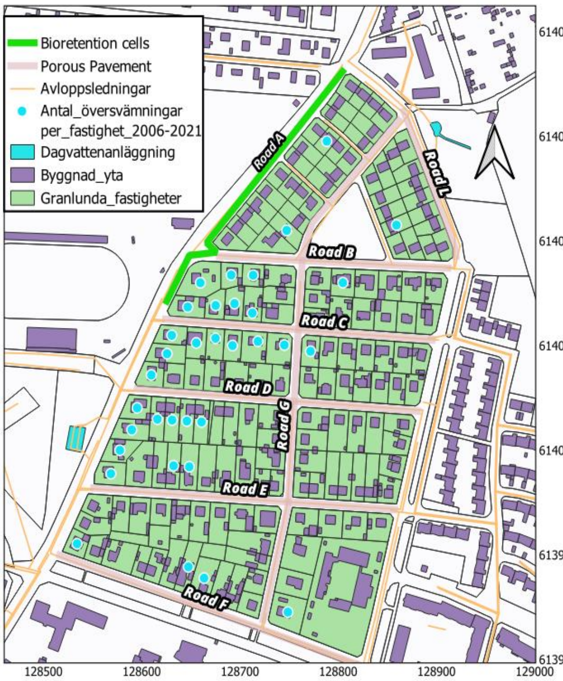


Figure 3.4.1: Deployment of BGG structures in the model.

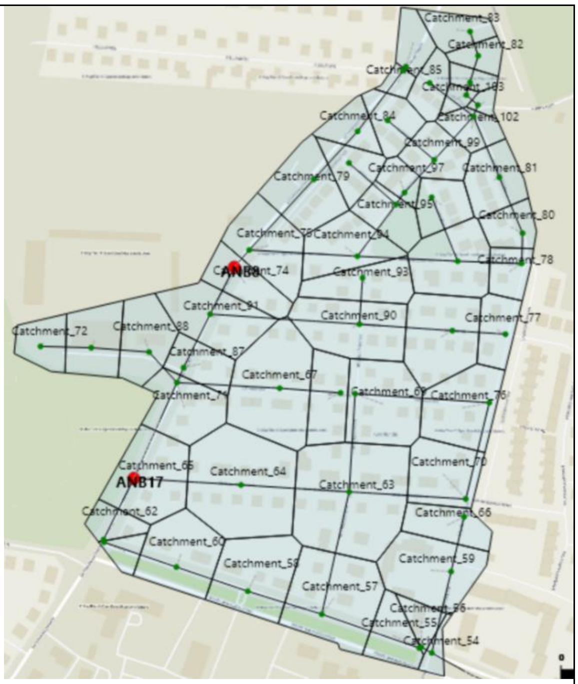


Figure 3.4.2: Catchment distribution of the model.

BGG structures in terms of bioretention cells are installed along road A in the model. It suggested only from catchment 85 downwards till catchment 74 which can be extended later upstream to increase the capacity of BGG structures later. The existing separate stormwater network is laid from catchment 91 downwards till catchment 62 along road A, therefore no BGG is suggested to deploy there again. In mike+ LID structures is possible to install as a property of the catchment only, so BGG structures are installed as segments in each catchment. The width of the cell was chosen depending on the available space and the required rootzone volume for trees as the main characteristic of BGG is the use of the subbase layer of the existing road to store stormwater and provide for vegetation and trees. A summary of the deployment of bioretention cells is presented below.

Table 3.5.1: Distribution and size of bioretention cells

Catchment	Number of Bioretention cells (Nos)	Width (m)	Area per unit (Sqm)	Collection Area per unit (Sqm)	The total area of bioretention cells (Sqm)	The total area of the collection (Sqm)	The total area of the catchment (Sqm)	% fraction of catchment for bioretention cells
Catchment_100	7	4	12	47	84	329	2492	3.37%
Catchment_98	8	4	12	36	96	288	2347	4.09%
Catchment_85	1	4	72	320	72	320	735	9.79%
Catchment_84	9	4	12	48	108	432	1963	5.50%
Catchment_79	18	4	12	64	216	1152	4715	4.58%
Catchment_75	28	4	12	51	336	1428	4800	7.0%
Catchment_74	6	2	6	120	54	720	2927	1.84%

Porous pavements with a storage capacity like BGG were suggested to be deployed at roads B, C, D, E, G, and L which is presented in the above figure with a transparent reddish color. Porous pavement cells were suggested only over pedestrian and bike lanes and a maximum of one flexible lane which is mostly occupied by parking. A great advantage of porous pavement is it has a high infiltration capacity that allows stormwater to infiltrate through the pavement and pass to the storage layer thus following natural hydrology and diverting the stormwater away from the pipe system and reducing the load for the pipe system. The study area is a low to medium-load traffic and residential traffic area and the roads here can satisfy the required distance of porous pavement from wells, houses, and water tables. Deployment of the porous pavement and available road width are tabulated below.

Table 3.5.2: Distribution and size of porous pavement cells

Roads with Porous Pavement	Covered Catchments	Total Width of the road (including bike lane) (m)	Width of the porous pavement Cells (m)	Fraction of road width for PP (%)	The total surface area of porous pavement (Sqm)	Total collection area (Sqm)
Road B	94,92,78	11	2.5	22,72	607.5	2821
Road C	91, 90, 89, 77, 67	8.5	2.5	29,41	697.5	2981
Road D	87,76,71,69,68and 67	8.5	2,5	29,41	727.5	3144
Road E	70,65,64 and 63	8.5	2,5	29,41	915	3667
Road G	102,99,97,95,94,93, 90,69,63 and 57	8.5	3	35,29	1503	4430
Road L	102,81,80 and 78	10	3	30	486	1603

3.5 Boundary condition

As boundary conditions, rainfall data were used. A 10-year synthetic rainfall is used as a boundary condition provided by DHI. To assess the impact of climate change, a factor of 1.25 was used for rainfall for the simulation of climate factors. Real rainfall data for 2021 was provided by Trelleborg municipality which was used to see the impact of the presence of proposed LID structures under such circumstances. This rainfall data is presented in the photos below.

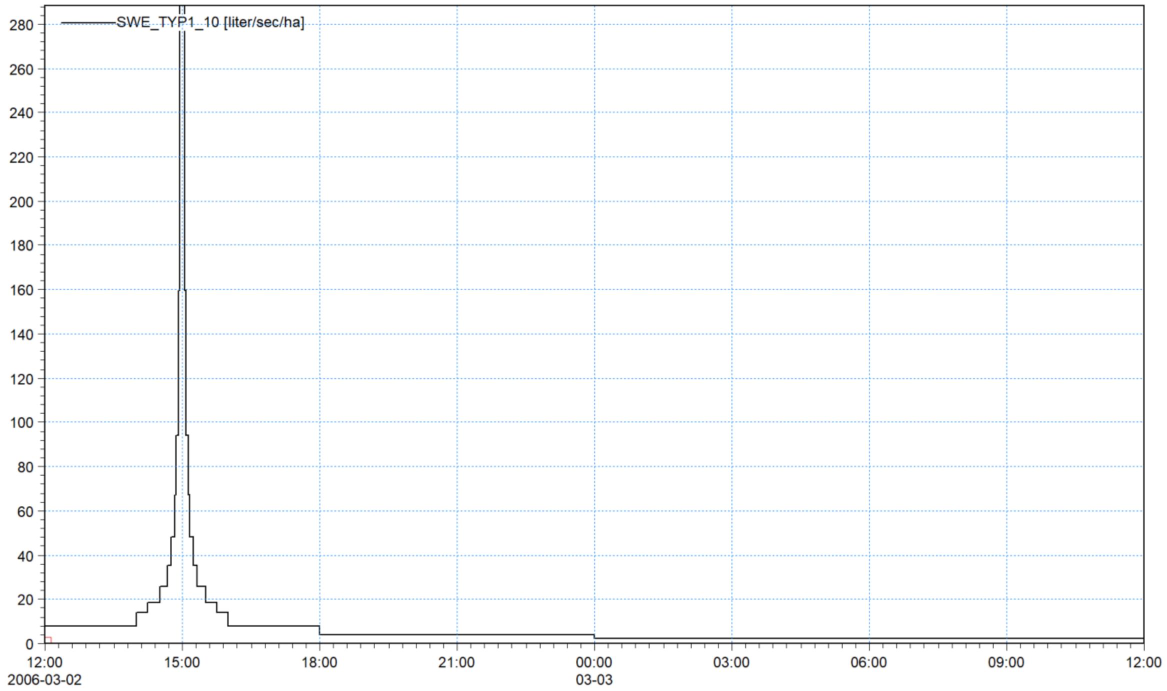


Figure 3.5.1: Graphical presentation of 10-year synthetic rainfall given by DHI. The X-axis shows the time, and the y-axis shows the rainfall intensity in l/s/ha

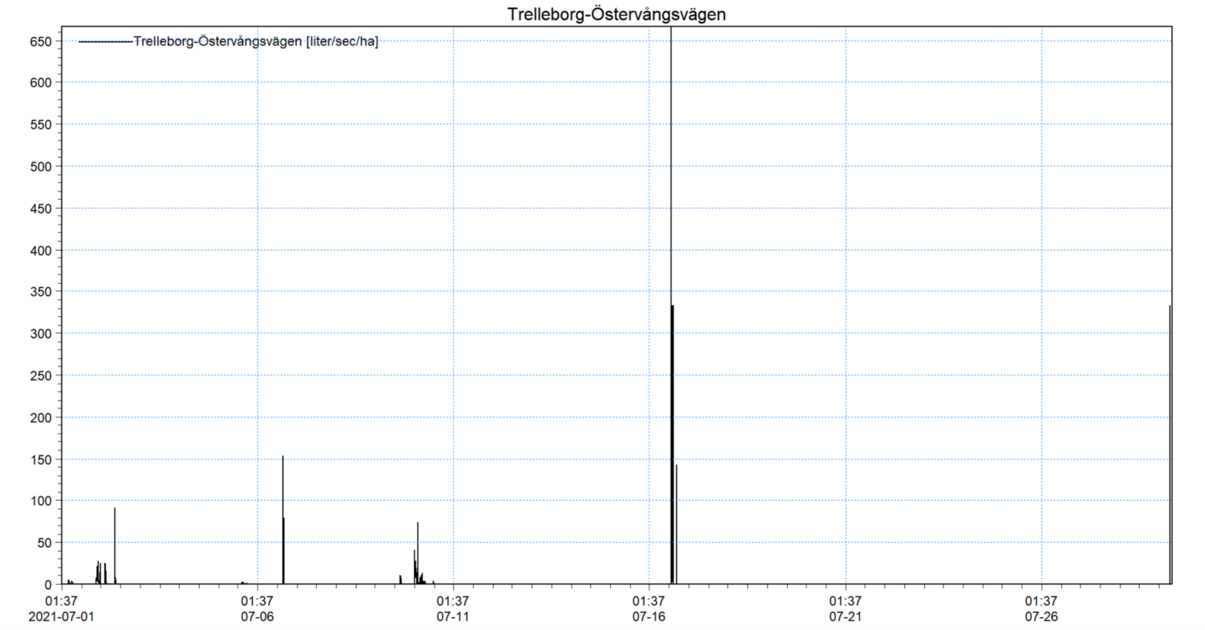


Figure 3.4.2: Graphical presentation of a real rainfall of 2021 given by Trelleborg municipality which ended up with a maximum claim of basement floods in the study area. The X-axis shows the time, and the y-axis shows the rainfall intensity in l/s/ha

For the 10-year synthetic rainfall total rainfall was 61.75 mm in 24 hours. Maximum intensity was 103.80 mm/hour or 288.33 l/s/ha. The real rainfall (2021) data provided by the municipality found a maximum total rainfall of 46 mm happened in 83 mins (1.5 hours). The return period of this rainfall event that happened in 2021 was found to be 50 years.

The model was run to test the sensitivity of different parameters of the LID structures and then with modified parameters to simulate BGG by bioretention cells. Then the model was run for a 10-year rainfall with climate factor and the real rainfall of 2021 for both the cases before the deployment of proposed LID cells and after deployment of them. Lastly, the model was tested to reduce the imperviousness resulting from roofs to test the performance of rain barrels or property owners' actions in stormwater management.

4. Results and discussions:

4.1 Distribution of BGG structures

After setting all geometric and hydraulic parameters depending on the sensitivity analysis and guidelines from different sources first BGG structures were deployed along different roads separately instead of deploying along all suggested roads together to see how much deployment is necessary and what should be the sequence of their execution. Here all analysis was done with 10-year synthetic rainfall with a climate factor of 1.25. In the profile plots below red dots along nodes are the critical levels for belonging node and when the maximum water level is above the critical levels in nodes, basement flooding is probable for households connected to the nodes. Profiles plots along roads A, B, and C are presented below as examples.

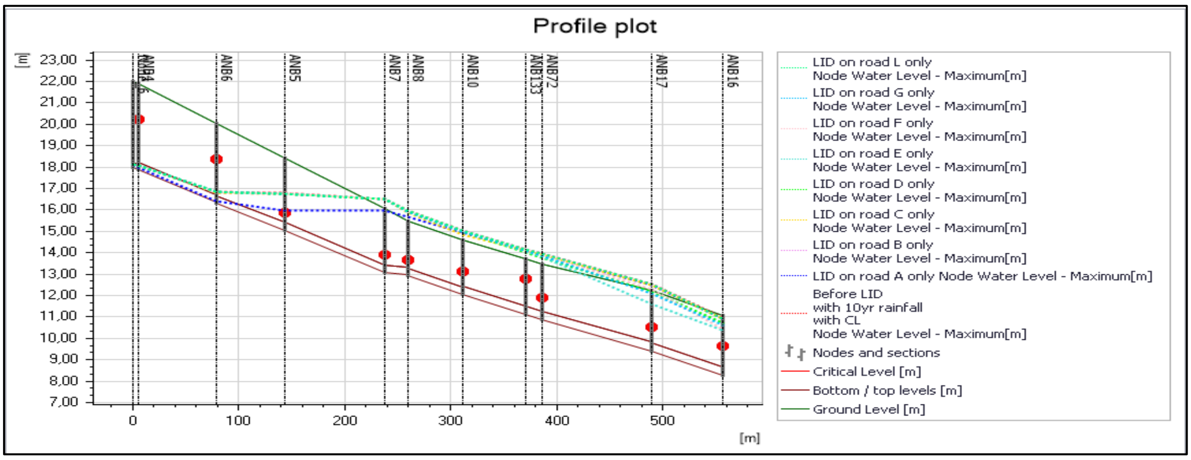


Figure 4.1.1: Profile along road A with node water level for BGG structures deployment along single roads

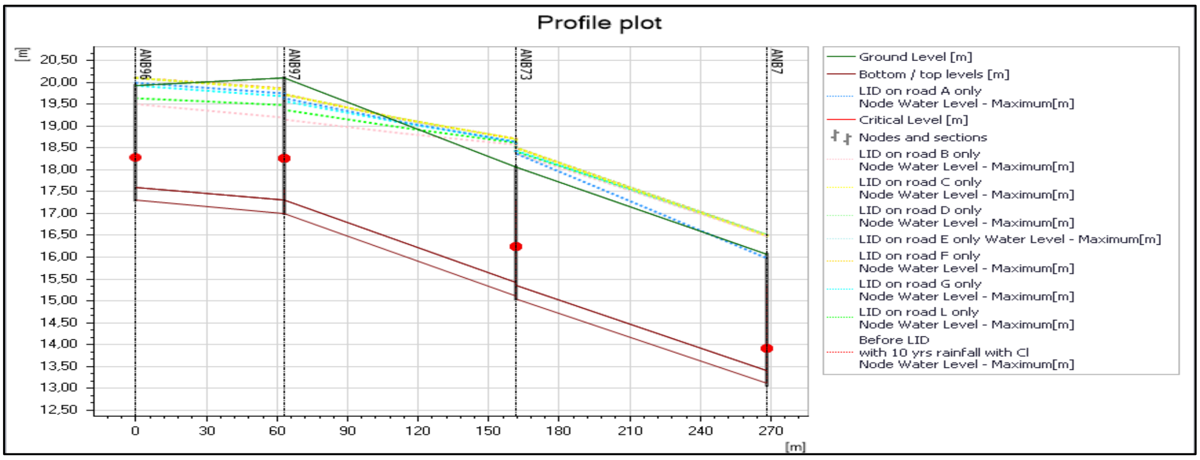


Figure 4.1.2: Profile along road B with node water level for BGG structures deployment along single roads

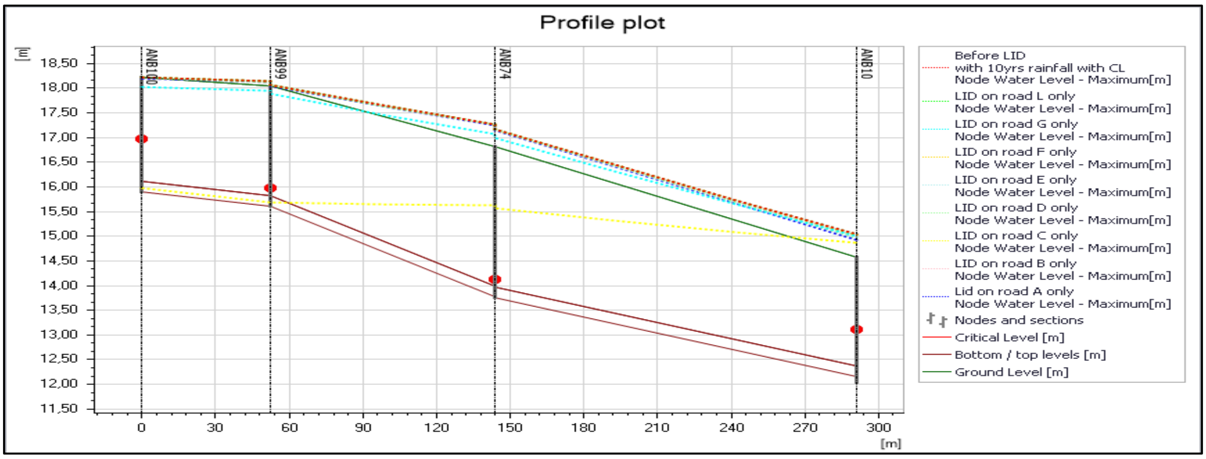


Figure 4.1.3 Profile along road C with node water level for BGG structures deployment along single roads

The results indicate that BGG deployment along one single road cannot solve the basement flooding for claimed households.

To prioritize the implementation, BGG structures were deployed first along roads A, G, and L as these roads carry upstream runoff with the underlying pipe network. The results showed no success in preventing basement flooding in flood-affected households. Then BGG structures were deployed along roads B and E in addition to the previous deployments. This time the profiles showed no basement flood along road F and a partial basement flood along road E. For the next step, BGG structures were deployed along road C additionally. The result showed no basement flooding along roads E and C and B but the water level is still above the critical level for two nodes named ANB71 and ANB72 which may cause basement flooding for 7 households in neighborhoods. Finally, BGG structures were deployed along the western part of road D as the pipe network here with the mentioned nodes above does not convey runoff from the catchments attached to the eastern side of rad D, which is clear in the node distribution in Figure 3.2.2. Profiles along roads F, E, B, C, D, and A are reported below with gradual deployment of BGG structures.

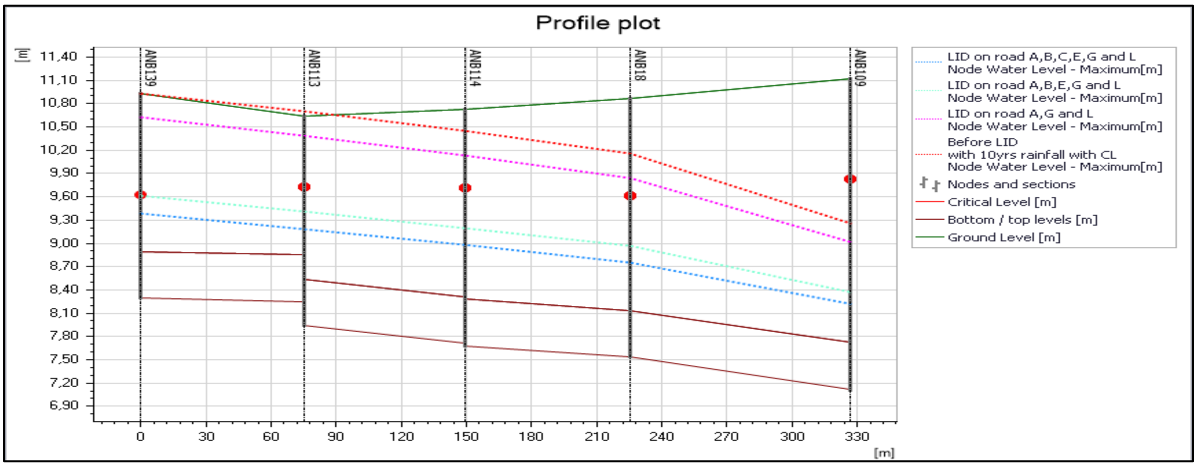


Figure 4.1.4 Profile along road F with node water level after deployment of BGG structures along several roads.

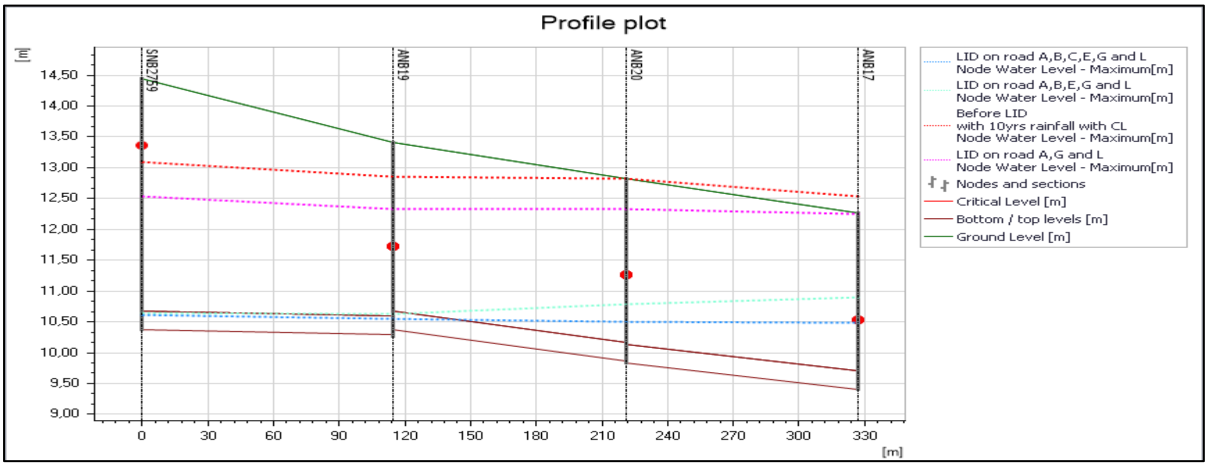


Figure 4.1.5: Profile along road E with node water level after deployment of BGG structures along several roads

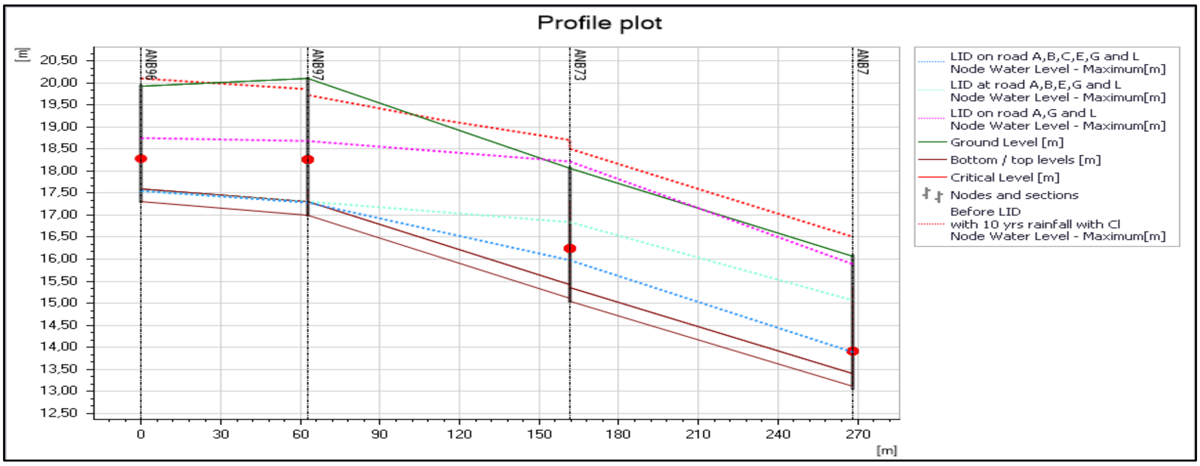


Figure 4.1.6: Profile along road B with node water level after deployment of BGG structures along several roads

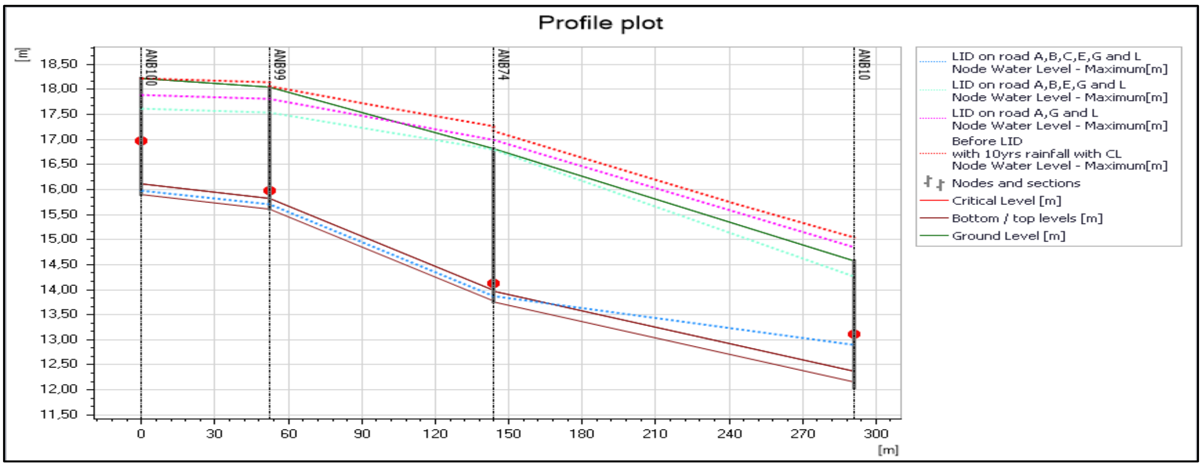


Figure 4.1.7: Profile along road C with node water level after deployment of BGG structures along several roads

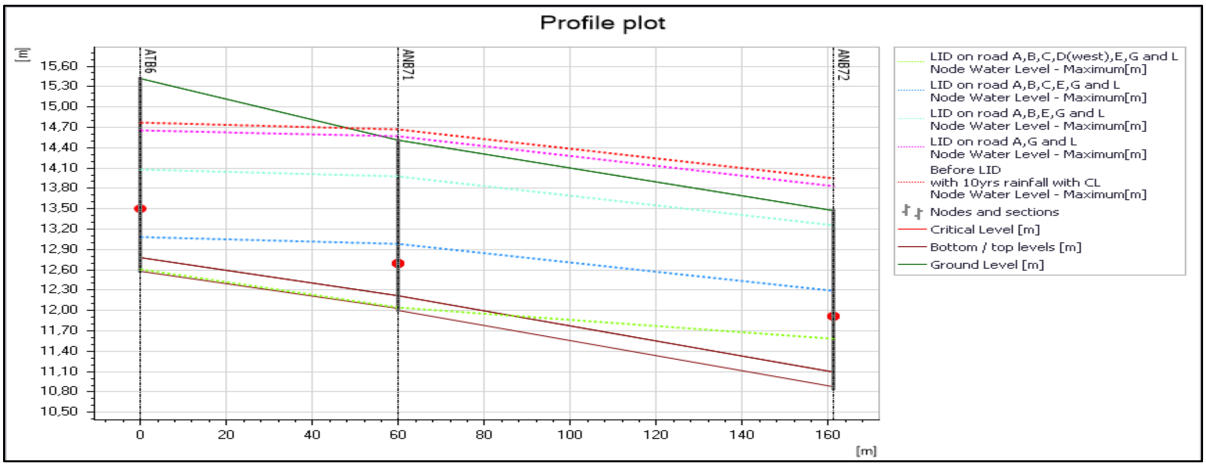


Figure 4.1.8: Profile along road D with node water level after deployment of BGG structures along several roads

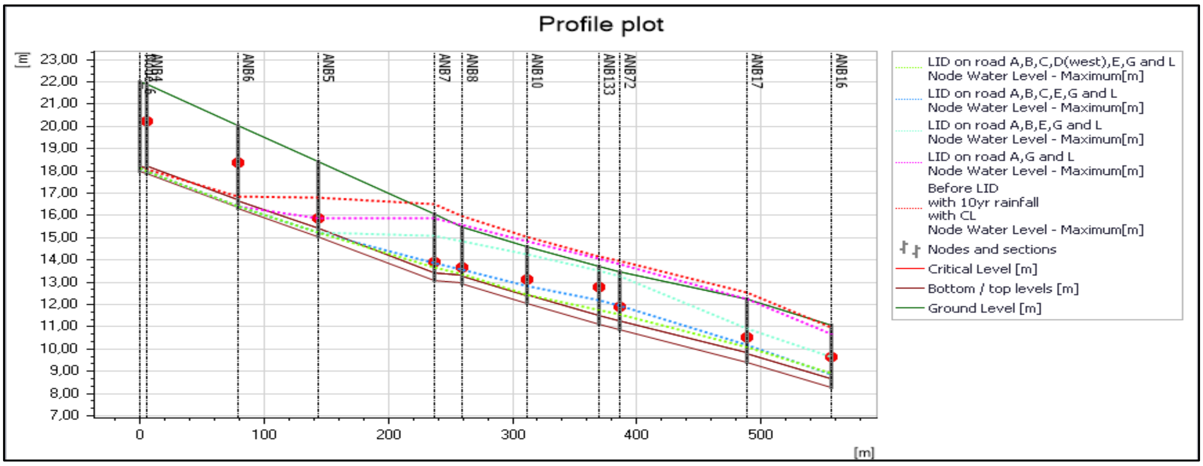


Figure 4.1.9: Profile along road A with node water level after deployment of BGG structures along several roads

All these tests and their results suggest prioritizing the execution of LID (BGG) structures as start with upstream of road A, and then roads G, L, B, E, and C, and lastly the west part of road D to make all the nodes and connections having water level below the critical level and thus solving the basement flooding in the study area.

4.2 Performance of BGG to reduce the risk of urban flooding and its consequences.

Total runoff produced by all catchments due to 10 years of rainfall events with/without climate factor was calculated for the conditions before and after the deployment of BGG and Porous pavement (PP) structures. The results are summarized in table 4.2.1 which shows how the BGG can significantly reduce the total runoff production in the catchments from the impervious area and thus can reduce the load in the pipe network. Here total runoff means the sum of runoff produced by all the catchments together.

Table 4.2.1: Summary of total runoff produced in the study area before and after BGG with 10-year synthetic rainfall.

	With existing system (m^3)	**With BGG (m^3)**	**Runoff reduction by percentage (%)**
Total Runoff (with 10-year rainfall without a climate factor of 1.25)	2397	1168	51
Total Runoff (with 10-year rainfall with a climate factor of 1.25)	3004	1586	52

Time series plots of several catchments in which BGG structures were deployed showed a significant change in flow rate in catchments as well. It reduces the flow rate almost to one-tenth of the flow rate without BGG. Which supported BGG structures to reduce the peak surface discharge. Two-time series plots for two catchments are presented below in figures 4.2.1 and 4.2.2 as examples to show how surface discharge changes with a significant reduction in peak discharge with BGG structures.

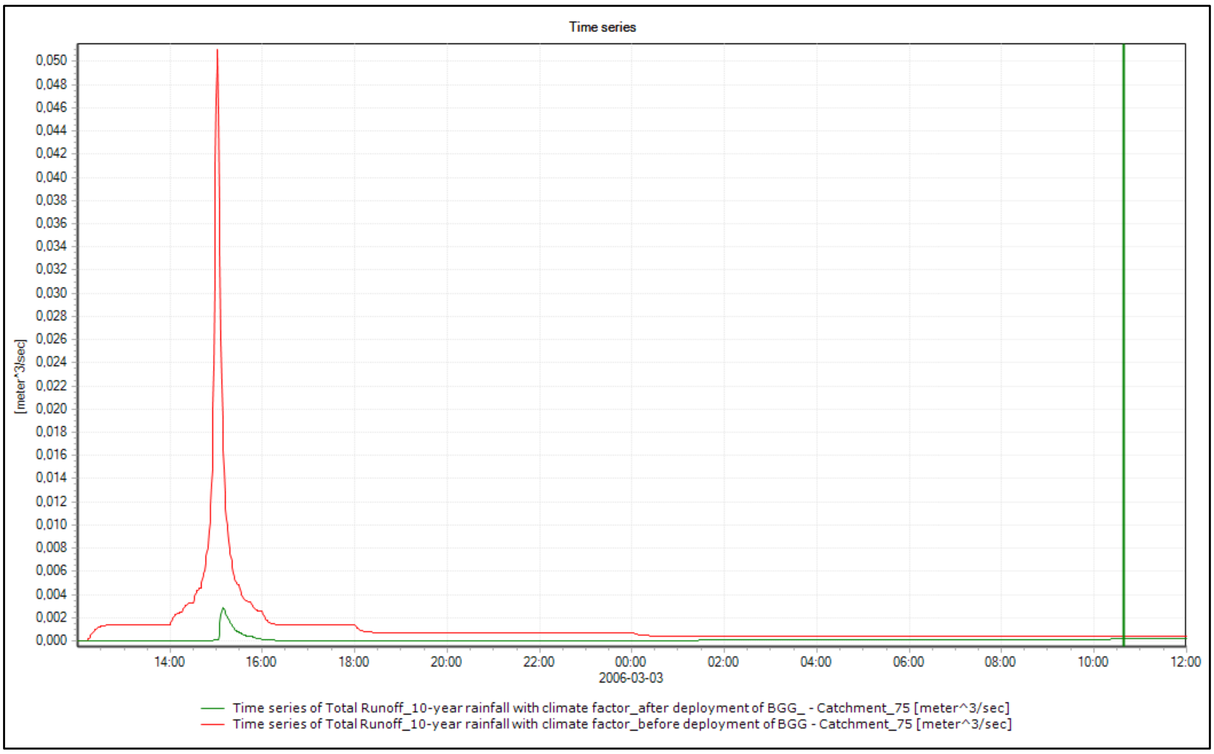


Figure 4.2.1: Time series of runoff in catchment 75.

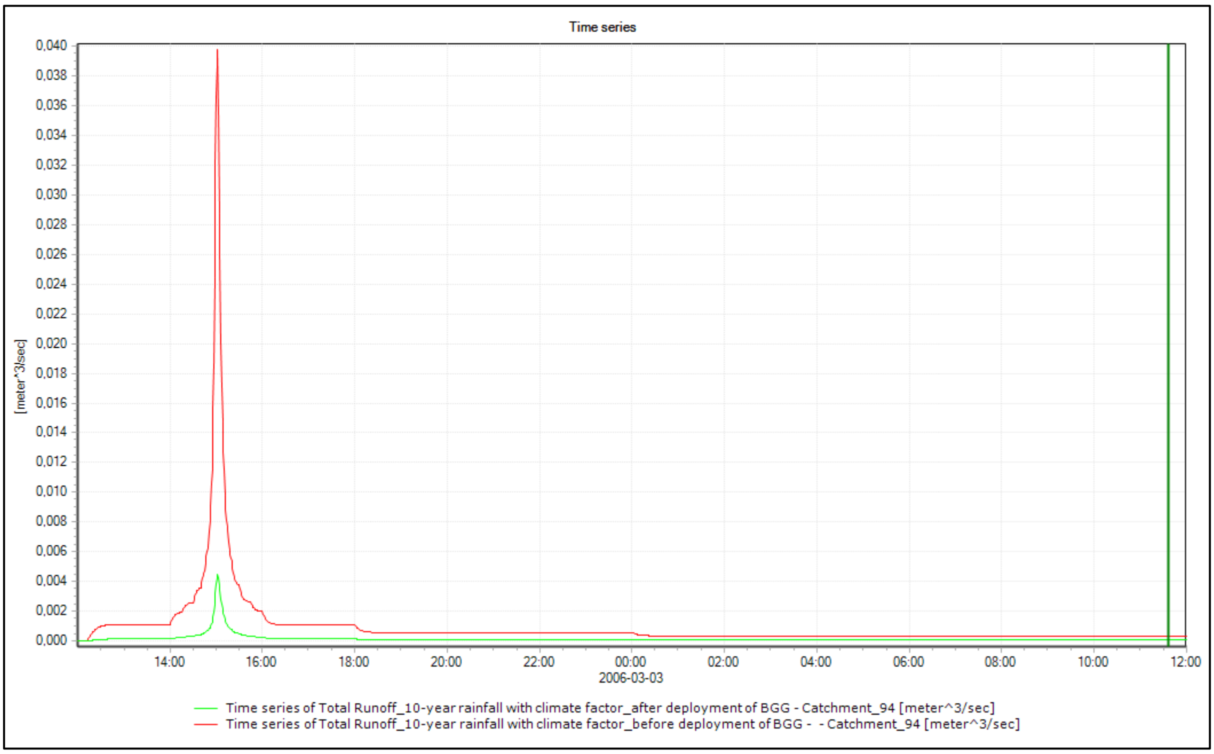


Figure 4.2.2: Time series of surface runoff in catchment 94.

This reduction in surface runoff makes the existing pipe network functional for 10-years rainfall and indicates a significant economic benefit. Compensating basement flooding with insurance costs a huge economic loss which can be reduced by the performance of BGG.

Apart from economic losses, the drowning of species, destruction of habitats, the proliferation of diseases, and destruction of ecosystems can result from a flood (*Livable-Streets-A-Handbook-of-Bluegreengrey-Systems-Version-2.0.Pdf*, 2020). Flooding may produce higher and erosive discharge on receiving bodies or downstream and may cause erosion and collapse of riverbanks which can lead to a further economic and environmental crisis (ibid). Particles washed and carried by the flood can sediment or high discharge can cause scouring in riverbeds which can cause risks to the already vulnerable aquatic and wildlife(ibid). The discharge rate and flow velocity through the outflow link with the existing drainage system and the proposed drainage system with BGG were observed with time series. The results are presented in Figures 4.2.3 and 4.2.4. The figures without BGG mean the existing drainage system and the results are made for the 10-year rainfall event with a climate factor of 1.25.

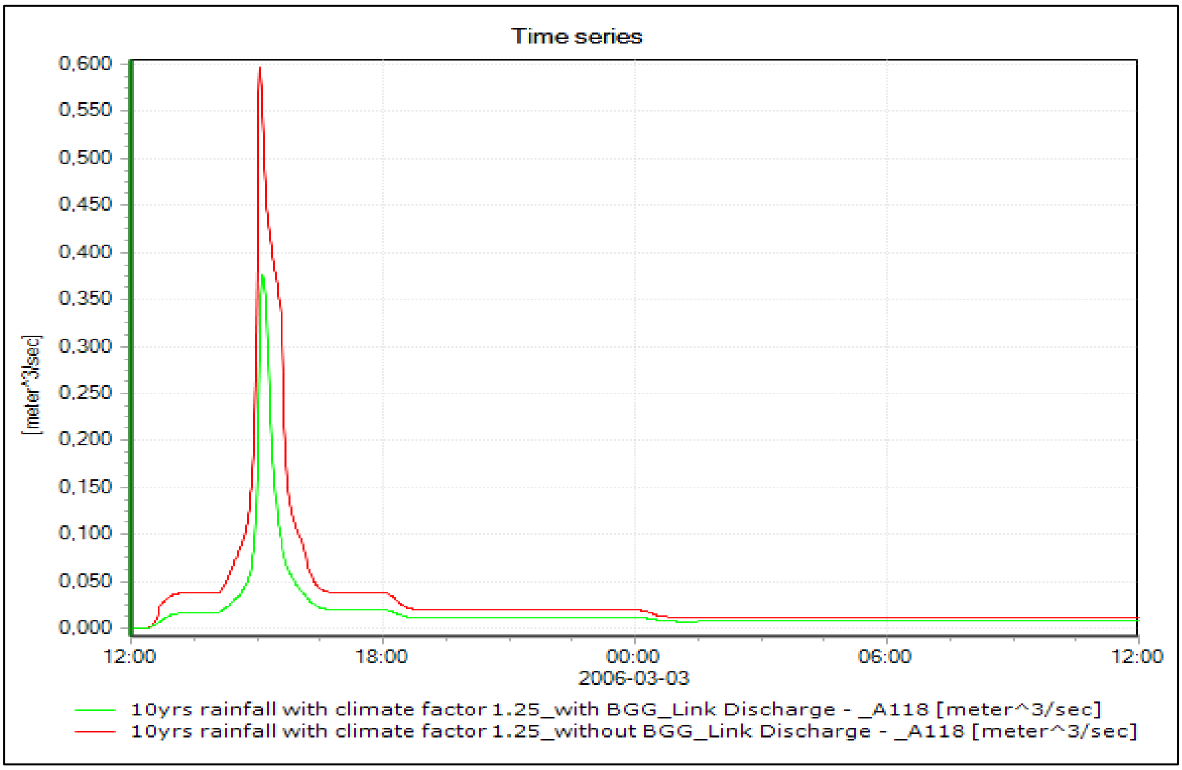


Figure 4.2.3: The discharge rate through the outflow link (link_A118) shows the discharge from the study area.

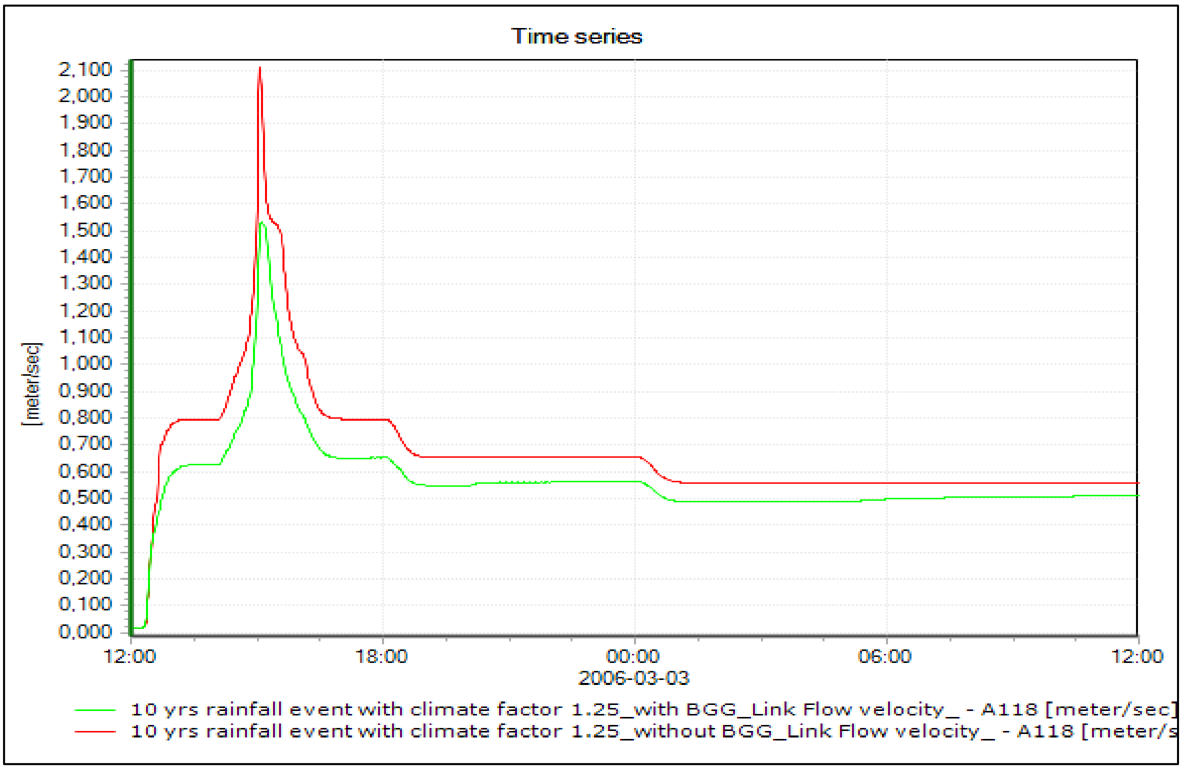


Figure 4.2.4: The flow velocity through the outflow link (link_A118) shows the outflow's flow velocity.

The results showed a significant reduction in both the discharge rate and the flow velocity. The discharge rate was reduced and became smoother and more regular for other links in the model for the study area as well. Figure 4.2.5 shows the discharge rate through link_9 which was chosen randomly in the study area to show the reduction of discharge rate. The results above indicated success in dissipating all the above consequences of urban flooding with the reduction of surface runoff.

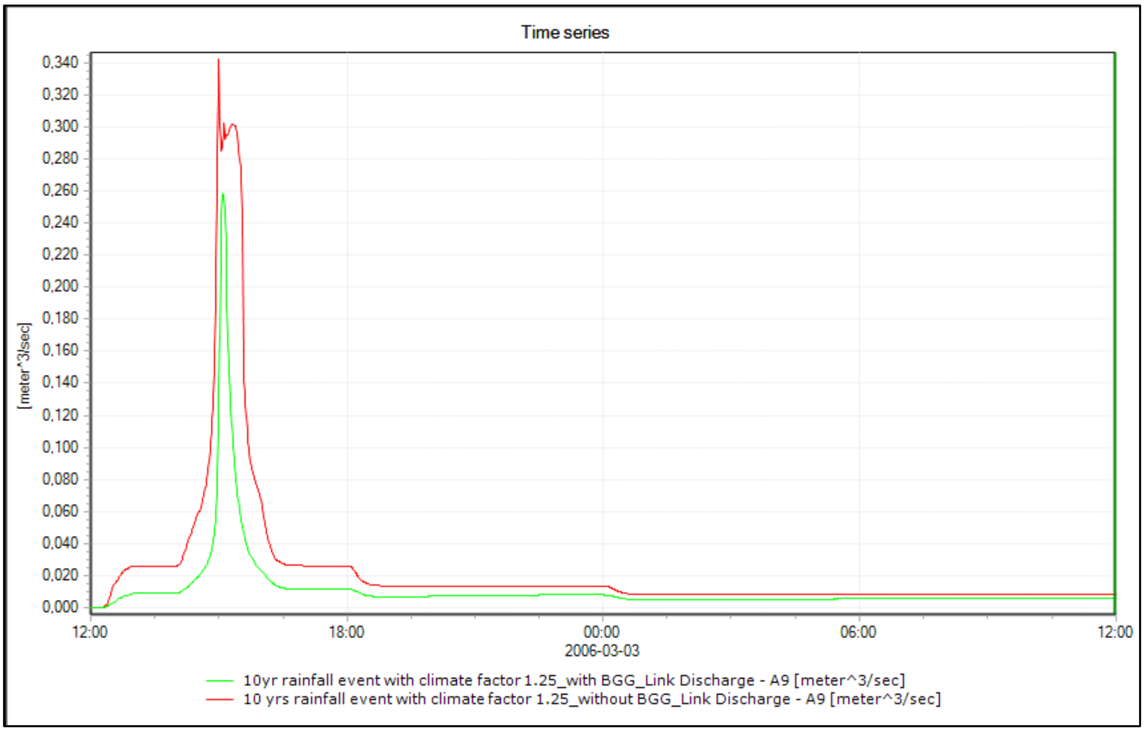


Figure 4.2.5: Discharge rate of the flow through the pipe link A9 showing smoother discharge rate with BGG structures.

Deployment of BGG reduces runoff by delaying a large portion of stormwater (by storage) and thus enhancing the natural hydrological cycle. The following pie charts illustrate how BGG can mimic the natural hydrological cycle components. Mike+ counts evaporation, transpiration, leakage, and infiltration from the system to the native soil as a loss.

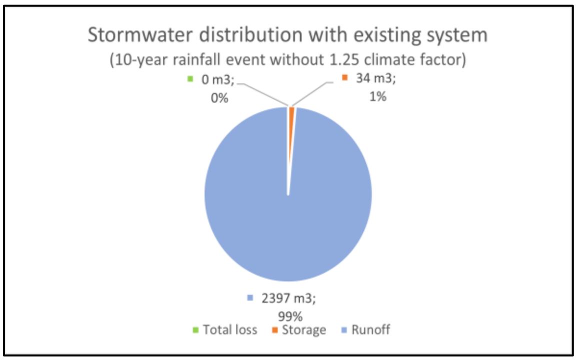


Figure 4.2.5: Distribution of stormwater for 10-year synthetic rainfall with the existing drainage system for the overall model.

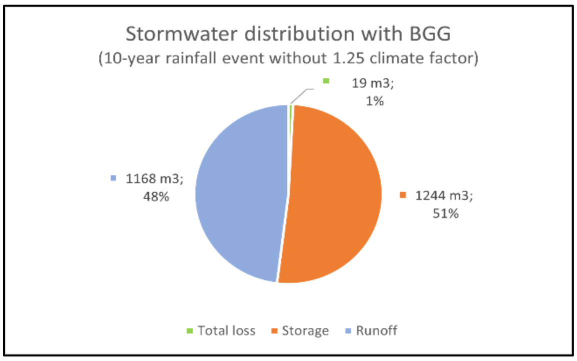


Figure 4.2.6: Distribution of stormwater for 10-year synthetic rainfall with the BGG for the overall model

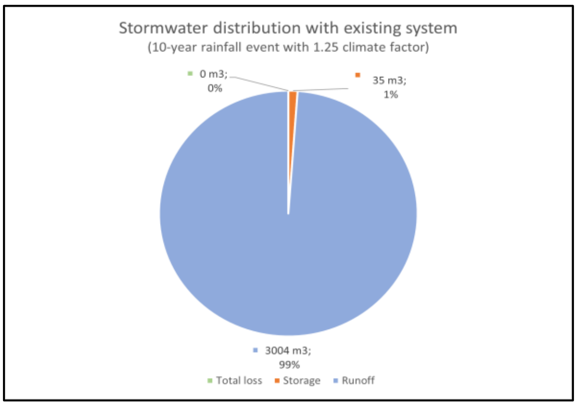


Figure 4.2.7: Distribution of stormwater for 10-year synthetic rainfall with a climate factor of 1.25 with the existing drainage system for the overall model.

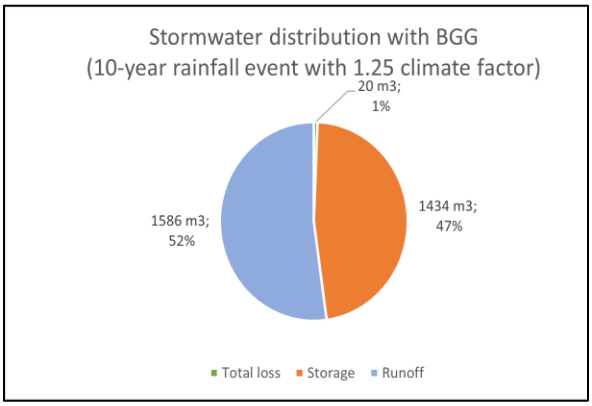


Figure 4.2.8: Distribution of stormwater for 10-year synthetic rainfall with a climate factor of 1.25 with the BGG for the overall model.

4.3 Capacity of installed BGG structures

The capacity of deployed BGG structures was assessed by how the BGG structures distribute the total inflow coming in the deployed structure. One part of the total inflow coming to the BGG structure infiltrates in deep soil, one part is stored in the structures and the rest of the water goes back to the existing pipe system as runoff. The results, presented in table 4.3.1 show the capacity of total deployed BGG structures to distribute the total inflow coming into the structures in the above-mentioned three phases.

Table 4.3.1: Runoff reduction Capacity of BGG for different rainfall events.

Rainfall	**Total inflow (m^3)**	**Infiltrated (m^3)**	**Surface runoff (m^3)**	**Drain outflow (m^3)**	**Final storage (m^3)**
10-year rainfall with climate factor 1,25	1655	20	56	174	1405
50-year rainfall	2016	285	68	344	1319

Two pie charts were made to show the capacity of deployed BGG structures to distribute total inflow coming into it for 10-year and 50-year rainfall respectively, which are represented in Figures 4.3.1 and 4.3.2.

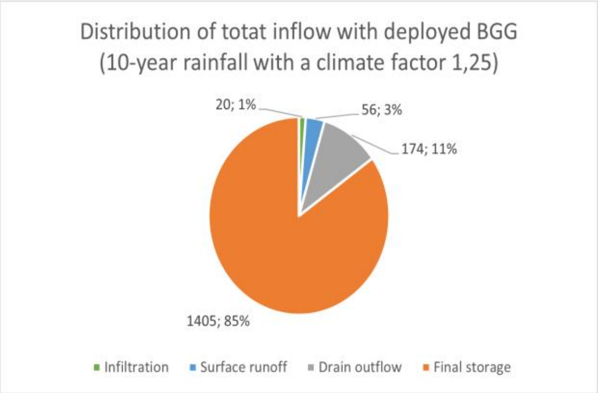


Figure 4.3.1: Distribution of total inflow with deployed BGG (for 10-year rainfall event with climate factor 1,25)

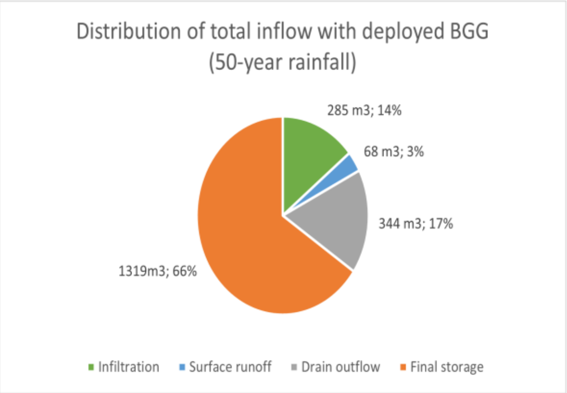


Figure 4.3.2: Distribution of total inflow with deployed BGG (for 50-year rainfall event)

Results also show that BGG structures can store a large amount of total inflow and thus reduce the runoff or inflow in the pipe network. This stored stormwater can be used by the vegetation and trees during dry periods to ensure healthy green space in urban areas and the excess water can be discharged to the existing pipe network after the storm in a controlled way by BGG's special control pits.

Finally, an approach was made to see the relationship between the fraction of impervious surface replaced with the BGG system and the reduction capacity of the surface runoff. The graphical presentation in Figure 4.3.3 below shows this relation. Fractions of the impervious surface replaced with the BGG system to make them pervious for all catchments were plotted against the surface runoff reduction capacity of the relevant catchment. It is important to mention here the graph was made with results from only a 10-year synthetic rainfall event with climate factor 1.25 and in the case study area no catchment had a slope of more than 5% and all the connections between the two adjacent nodes were also within a maximum of 5%.

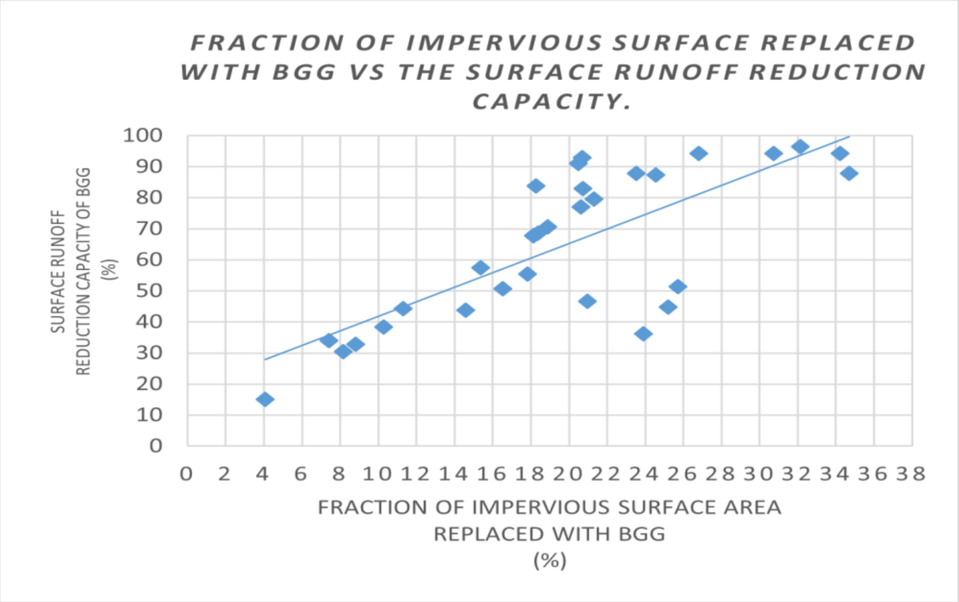


Figure 4.3.3: Graphical presentation of the relation between the fraction of impervious surface replaced with BGG and the surface runoff reduction capacity.

The trend line in the above graph signifies that 50% of surface runoff reduction in the case study area is possible by replacing about 14% of the impervious surface area and the replacement of one-third of the existing impervious area can reduce the surface off more than 90%.

4.4 Performance of proposed BGG structures under real rainfall of 2021

The proposed sustainable design structures showed great results to dissipate the basement flooding under severe rainfall events which were experienced by the case study area in 2021. An analysis was done to investigate the equivalence of that rainfall in terms of return period and found it to be a 50-year rainfall event. The experiment result showed the proposed BGG structures to make the existing pipe network functional for 10-year. rainfall to prevent basement flooding can successfully manage the stormwater for a 50-year rainfall event as the maximum water level in nodes is quite below the critical levels of relevant nodes. Three profiles are presented in the following figures 4.4.1, 4.4.2, and 4.4.3 to show the capability of the proposed BGG as all the profiles showed success in preventing basement flooding.

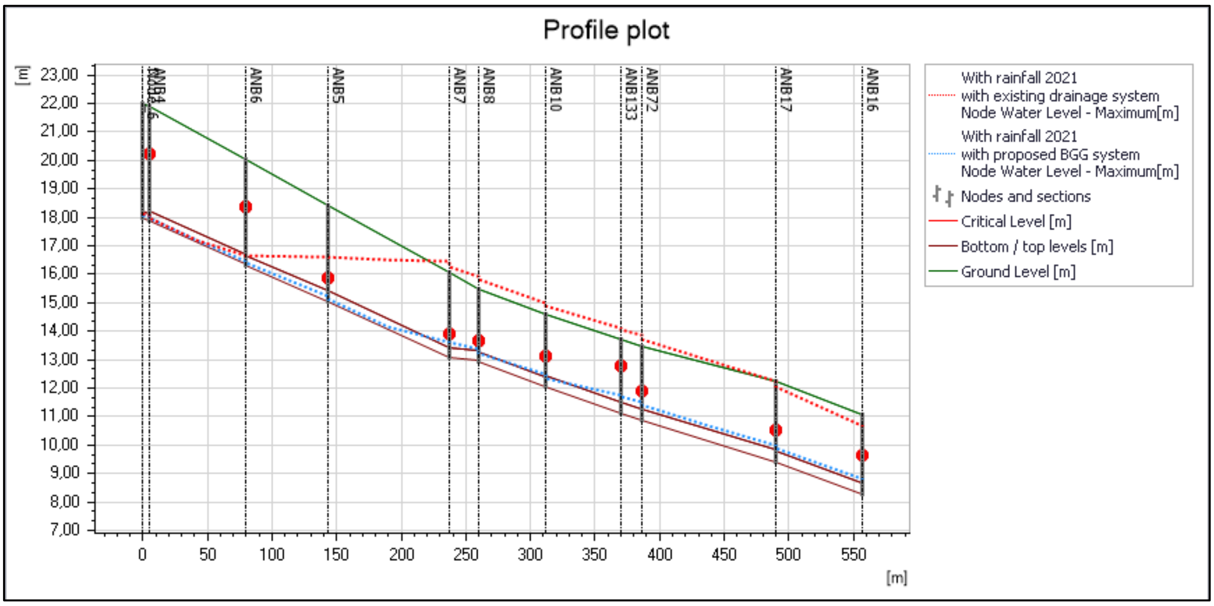


Figure 4.4.1: Long profile along road A showing the performance of BGG to mitigate basement flooding.

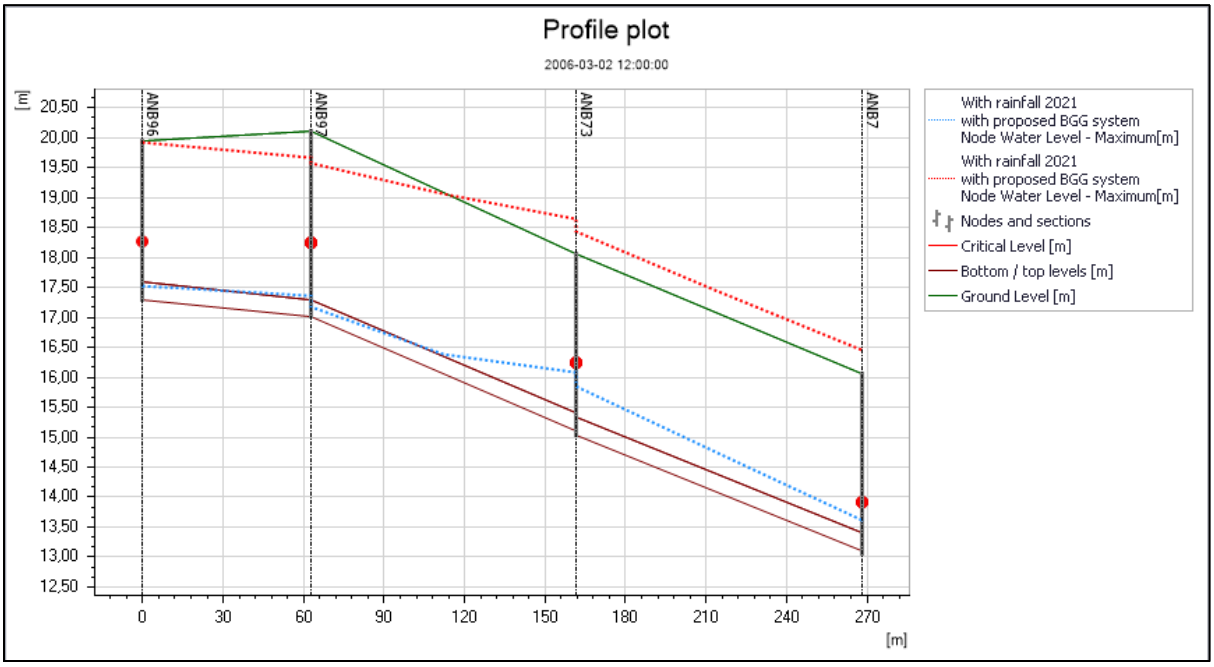


Figure 4.4.2: Long profile along road B showing the performance of BGG to mitigate basement flooding with a 50-year rainfall event.

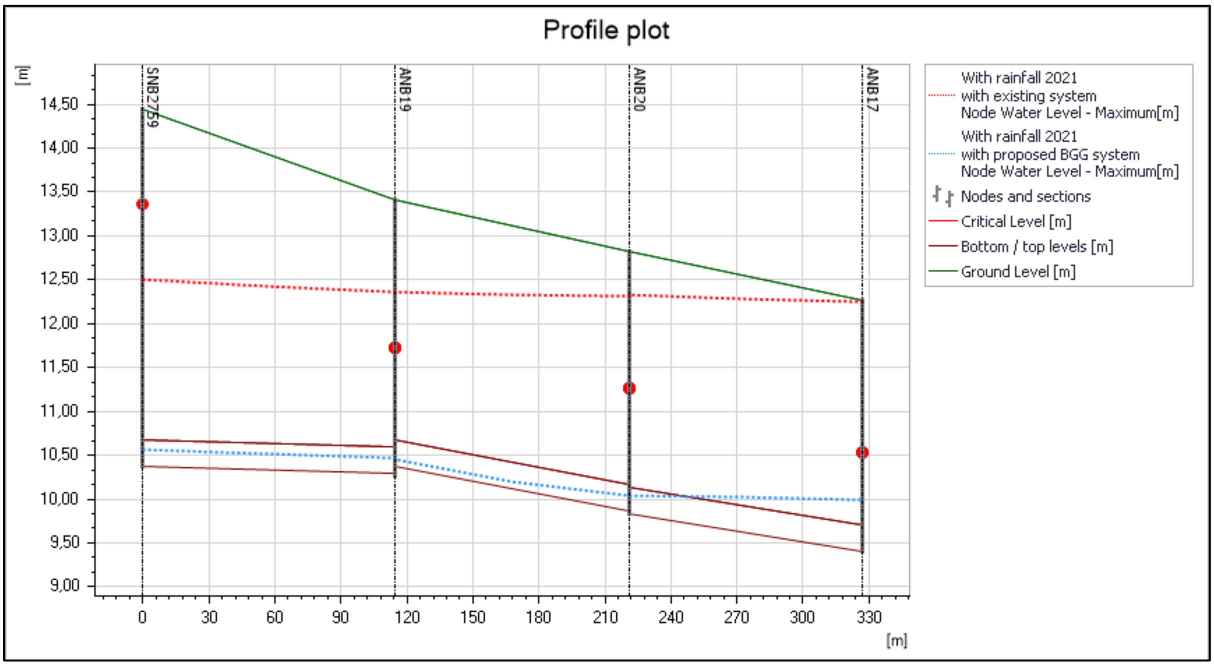


Figure 4.4.3: Long profile along road E showing the performance of BGG to mitigate basement flooding with 50-year rainfall event.

The total runoff from the whole model for the real rainfall event of 2021 was computed to be 3845 m^3 whereas it was reduced to 2007 m^3 when the model was run with deployed BGG. This result summarized a reduction of surface runoff by 48% with the deployed BGGs which were deployed to dissipate basement flooding with the 10-year rainfall event. Stormwater distribution charts given below indicate the performance of BGG can be efficient under large rainfall events. It also bids the function of BGG to mimic the natural hydrological cycle by distributing the rainfall inflow in different components instead of producing a huge volume of surface runoff. The stormwater distribution capacity of the deployed BGG for the real rainfall event of 2021 is summarized below in the pie chart.

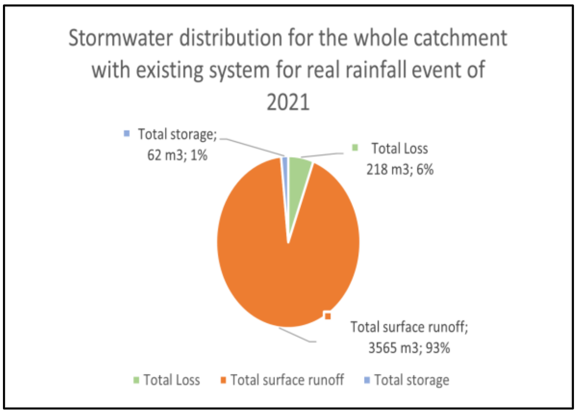


Figure 4.4.4: Stormwater distribution with rainfall_2021 without BGG

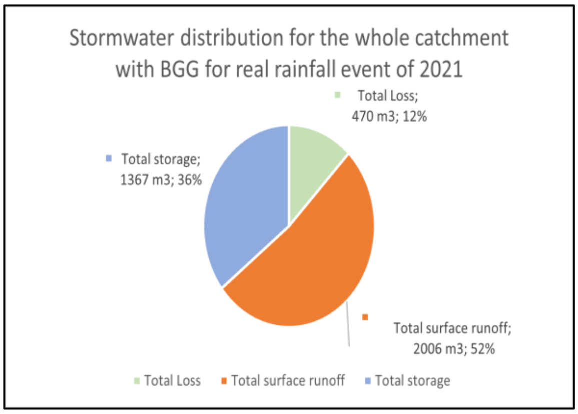


Figure 4.4.5: Stormwater distribution with rainfall_2021 with BGG

Time series plots for all the catchments with deployed BGG structures were observed to see the surface runoff flow for the catchments. Four time series plots of surface runoff for two catchments without and with BGG are presented below which showed BGG structures reduce the surface runoff peak significantly even with a large magnitude of rainfall as it was in 2021 in Trelleborg. Previously discussed stormwater distribution with the performance of BGG causes this significant reduction of runoff flow which can be a solution for surface flooding in urban areas also.

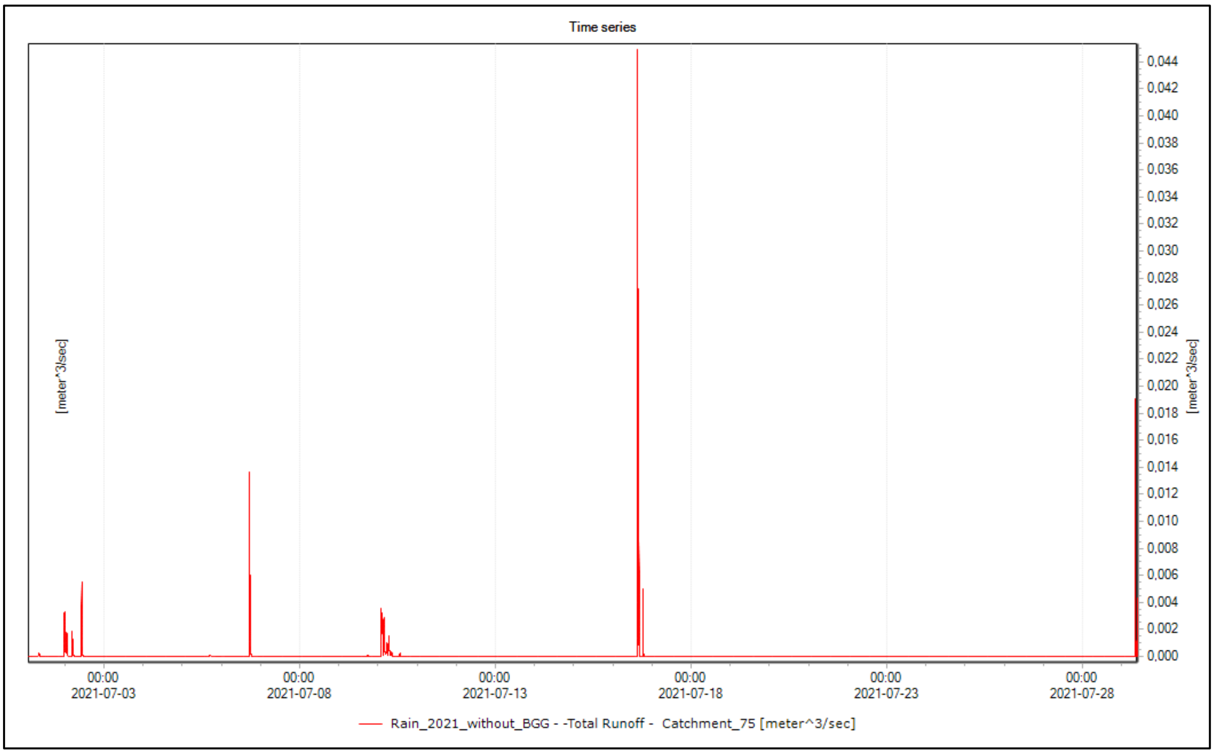


Figure 4.4.6: Times series of surface runoff in catchment 75 with rainfall_2021 without BGG.

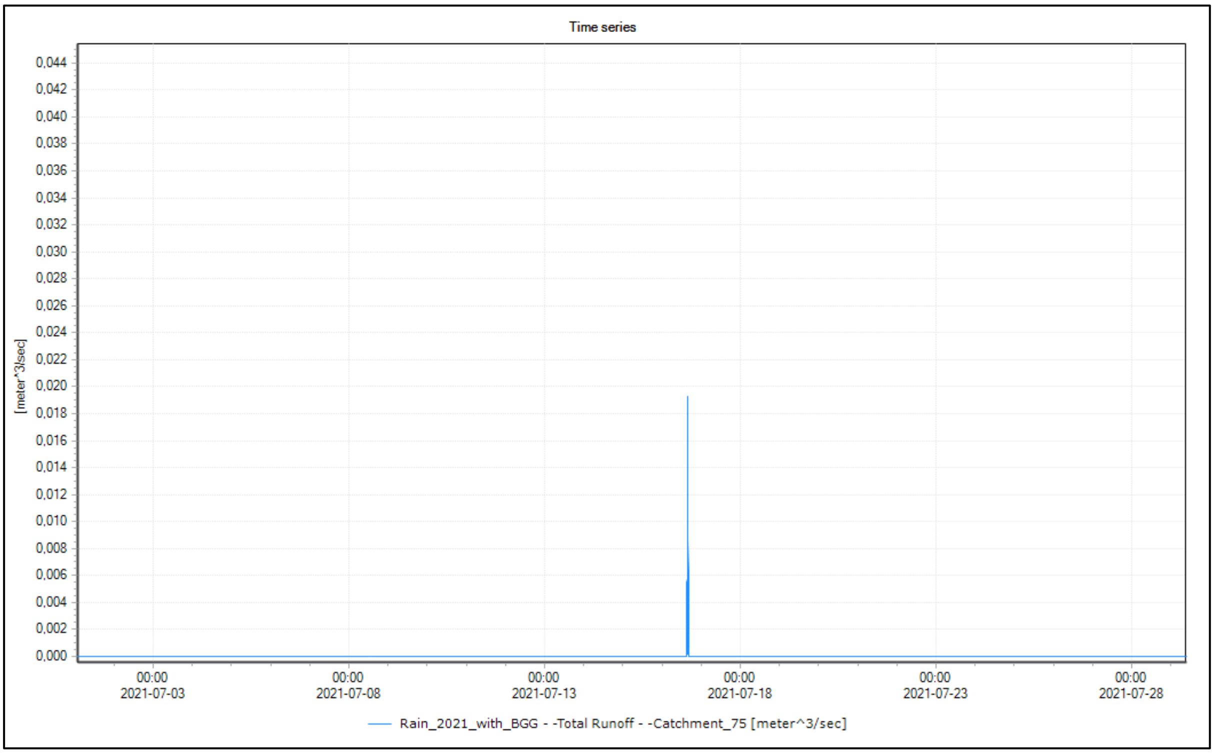


Figure 4.4.7: Times series of surface runoff in catchment 75 with rainfall_2021 with BGG.

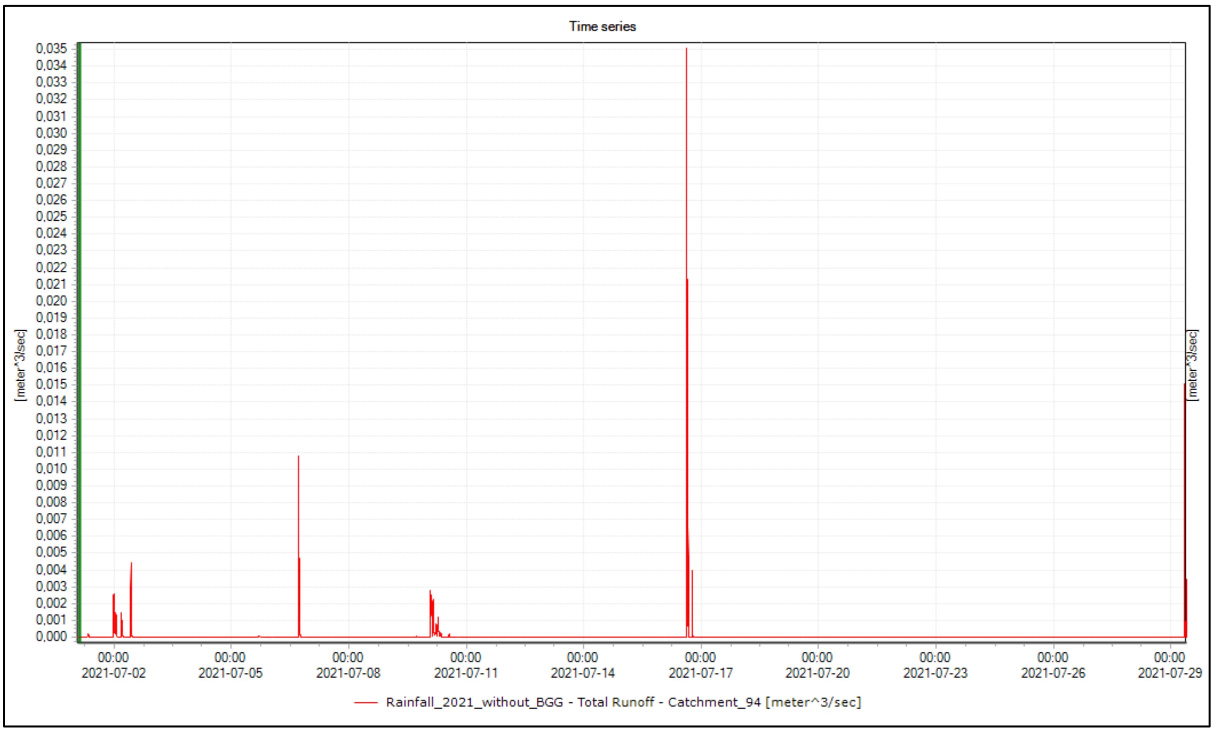


Figure 4.4.8: Times series of surface runoff in catchment 94 with rainfall_2021 without BGG.

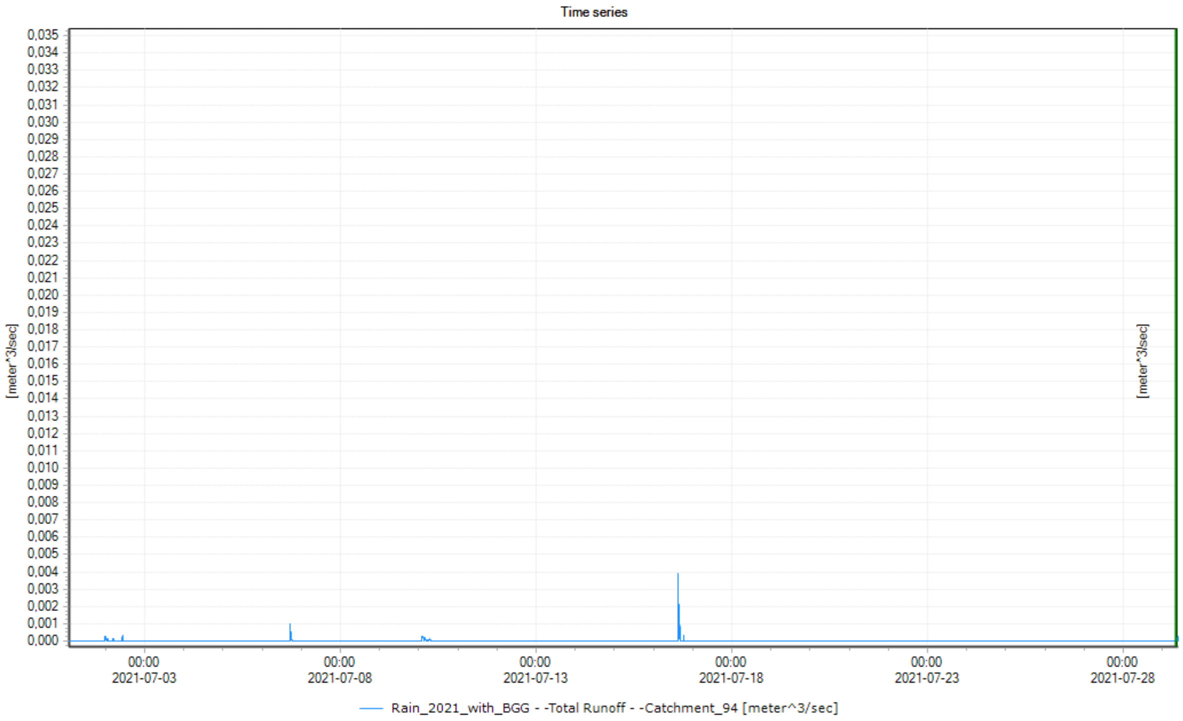


Figure 4.4.9: Times series of surface runoff in catchment 94 with rainfall_2021 with BGG.

The deployed BGG structures reduced the discharge rate and flow velocity through the pipe links and made them smoother when the model was tested with the real rainfall event of 2021. Figures 4.4.10 and 4.4.11 show the results for discharge rate and flow velocity analysis for the outflow of the study area.

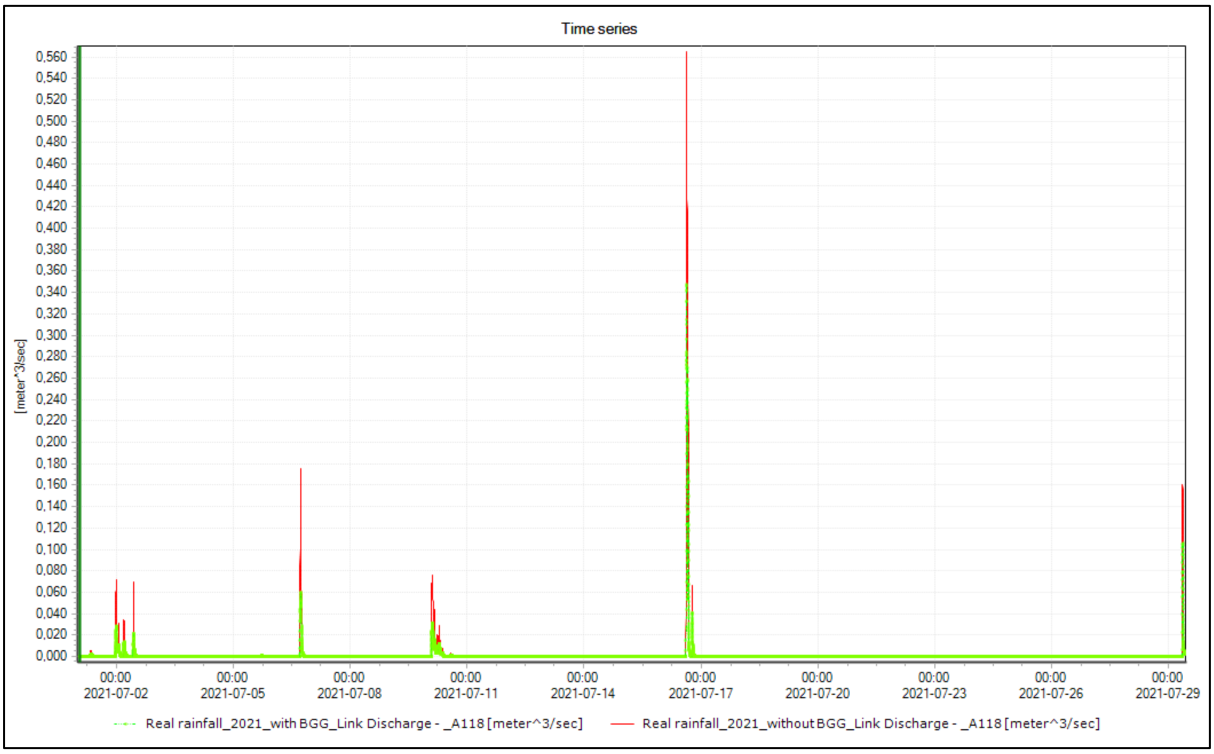


Figure 4.4.10: Discharge rate through link A118 showing the discharge rate for the outflow of the study area before and after the deployment of BGG structures.

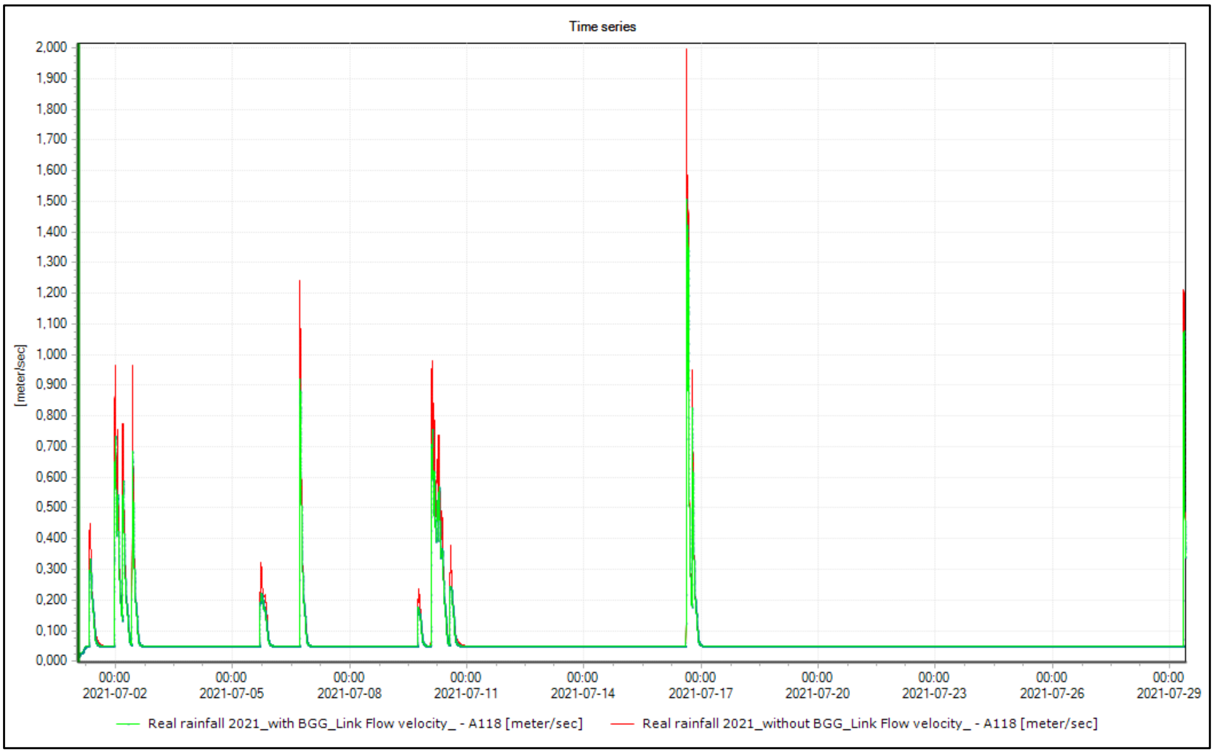


Figure 4.4.11: Flow velocity through link A118 showing the flow velocity of the outflow of the study area before and after the deployment of BGG structures.

4.5 Performance of source control SUDS and compare to BGG

In the theoretical background, it was mentioned that SUDS can be implemented on private lands instead of public land which is called source control. In this study, a model test was run to see how much private land-owned SUDS (source control) can help to reduce surface runoff compared to the SUDS implemented by a public authority (BGG in this study). To perform this test, impervious surfaces owned by the private owners were disconnected from the existing pipe system. This test was performed only for 10-year synthetic rainfall with a climate factor of 1.25. The result indicated a 23% decrease in surface runoff for the whole study area but a failure to reduce the water level enough to prevent basement flooding. With the existing condition, the surface runoff volume was 3039.4 m^3 whereas the surface runoff was reduced to 2319 m^3 for the total study area. In this test, the reduction of impervious surfaces by disconnecting private land sources was computed to be 23%. All profile plots showed the same results for node water level, they were reduced but not below the critical level. Profile along road B is presented below as an example to visualize the node water level with source control SUDS. Results for individual catchments indicate that the capacity to reduce surface runoff by source control varies from catchment to catchment. Catchment formation i.e., how much impervious surface the catchment has, the size of the catchment, and rainfall determines the amount of runoff reduction by source control.

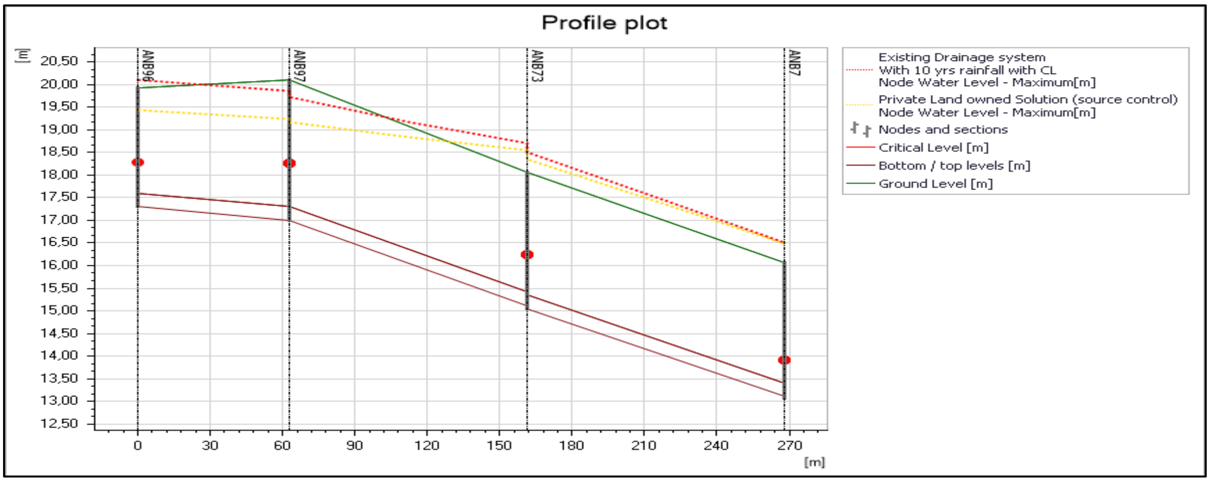


Figure 4.5.1: Profile plot along road B showing water level in nodes with source control SUDS

5. Limitations

Basement levels for the households, drain wells, connection of households to the pipe network, and some other relevant data for the study area were provided by the municipality and they were used to define the critical level in nodes in the model. The collection date of those data was unknown. Any change in those data could cause a change in critical level which can change the result to prevent the flood.

In Mike+ only the Kinematic wave runoff model (model B) is allowed to use and do performance for LIDs or sustainable drainage design structures. In model B LID structures use the inflow from only impervious surfaces in the catchment. So, all the results above were made when only the contribution from the impervious surfaces was considered to contribute to the pipe network system. If the soil of the pervious surface fraction of the catchments becomes saturated due to any rainfall event, then they can also contribute to surface runoff for the pipe network system which was ignored in this model study. In that case, only the percentage of runoff reduction capacity can be changed.

In this study, the function of the BGG system and its dimensions were simulated by simplification to use in the conceptual model.

Water quality analysis was not done in the model for this study. But in the mechanism of the BGG system stormwater passes through several layers which have the potential to remove suspended particles and debris. As the stored water is being consumed by plants and vegetation nutrients like Nitrogen and phosphorus are expected to be removed theoretically. As a result of the natural process, BGG is expected to do 70-80% treatment for stormwater.

The results can vary depending on the parameters, dimensions, slopes, and other factors in real practice. However, the performance of the BGG is not expected to be reduced as a conservative approach was used in this study. As already mentioned before, the evaporation is counted as loss by Mike+ so the evaporation volume for the reality could differ from that of the model result.

6. Conclusion

The results of this study concluded that BGG is an efficient and holistic approach to improving the urban drainage system and mitigating basement flooding and overall urban flooding issues. Sensitivity analysis and distribution analysis of the BGG structures suggested the importance of maintaining different parameters, especially infiltration capacity, porosity, depth of soil surface or substrate, depth of storage layer, and the distribution of BGG structures to mitigate basement flooding. BGG structures are functional in both cases separately or continuously.

The results also showed the size of BGG structures (number and total surface area), size, and formation of catchments determine the surface runoff reduction capacity of BGG structures. The magnitude and duration of rainfall also cause variations in reduction capacity. BGG structures infiltrate the rainfall inflow with their infiltration capacity and store a fraction of the inflow in their storage layer which can be provided for vegetation and plants and trees to ensure healthy green life in urban areas. As a result, BGG can be considered a carbon sink in urban areas also. The BGG structures mimic the natural hydrological cycle and make the stormwater an asset instead of a problem. The performance of BGG structures to dissipate basement and urban flooding is thus not limited to a 10-year rainfall event, rather are successful in mitigating urban flooding in case of a 50-year return period rainfall. The significant characteristics of BGG are it does not need to change the landscape and it does not need any additional space as it stores water in an open subbase layer of roads to provide for healthy green lives while maintaining the load-bearing capacity for traffic.

The technique used by BGG to manage stormwater sustainably enhances the circular approach instead of the conventional one-way approach. The stormwater is being preliminary treated by filtration through different layers of BGG and the water is being reused by plants which are ensuring heat and carbon sink in urban areas. BGG suggests waste hierarchy which means the reuse of resources to ensure optimal outcomes with fewer resources, to apply for water resources management to make the stormwater resource instead of a burden or risk for the society and the environment. BGG can support the building of sustainable cities, the environment, and biodiversity along with climate adaptation.

Source control SUDS i.e., rain barrels or disconnection of impervious surfaces at sources can reduce the volume of surface runoff if the impervious surface fraction can be reduced. But this doesn’t have the same capacity as that of BGG structures.

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