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Dinithi Ranasinghe

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NTNU
Norwegian University of
Science and Technology
Faculty of Architecture and Design
Department of Architecture and Technology

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Effectiveness of innovative Green Roofs and its implications in Storm Water Management for Sustainable Development in Norway

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Master's in Sustainable Architecture
Submission date: June 2022
Supervisor: Rolf André Bohne
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Summery

This report reviews the effectiveness of green roof configuration and geometry to be mitigated with climate change tipping points. The rapid urbanization in cities indicates an increased exposure with impermeable roof surfaces to 35% - 45% of land area, which increases the risk of exceeding the design parameters of the existing combined stormwater management system in Norway. The city transformation with green roofs holds numerous benefits in reversing planetary boundaries and this study has concluded with a positive effectiveness in CO_2 *reduction, hydrological performance, and direct effect for urban heat island effect. The results were found to be more effective for green roofs as a LID, when applied with mild or moderate precipitations in terms of water retention and detention. The increase of the precipitation has shown decrease of the detention ability while retention value decreases as a fraction of the precipitation. However, green roofs show more relevance as an integrated layer or the first step, in the stormwater management system in Norway to act as a method of promoting evapotranspiration as a mitigation to reduce urban heat island effect with latent heat flux as it increases with the water presence increases and reducing stormwater flow peaks by around 80% for increased future precipitation compared to a conventional roof. The volume reduction by retaining water in green roofs as a fraction of the total precipitation, which ranges from 40% to 20% as the precipitation increase from moderate to severe. Even though it can be expecting to have increased runoff volumes as the angle increases, the angle of the green roof shows no effect for the hydrological performance after exceeding the substrate thickness of 140 mm while impermeable roofs show a considerable rise of the peak runoff from around 25% - 30% as the angle increases. The transformation of cities with green roofs have shown a potential of influencing the increase of CO2 sequestration of dense urban cities with lack of spaces for trees, by around 7% CO2 sequestration increase with angular green roofs over flat green roofs. As the green roofs exerts extra structural loads on a building in retrofitting buildings in a city transformation, attention on reduction of structural loads through sloped green roofs has shown a 2% to 8% of reduction of deflection over deflection of a flat roof. Hence, according to the results obtained from this study, the effectiveness of angular green roofs shows higher ability than a flat green roofs and the importance of the green roof within the city scale beholds the fact that it shows enough relevance to be applied in building as a feature or the first step in storm water management process in Norway and the advantages have indicated as far more higher than minor disadvantages such as the cost and extra structural load on roof.*

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BERG - Bergen

IBC - International Building Code

IR - Impermeable Roof

GR - Green Roof

LID - Low Impact Development

TRD - Trondheim

Acknowledgement

This has been one of the best times that I had in my academic life which was inspiring and challenging. I wish to thank all my colleagues, teachers, family, and friends who have provided me the support and guidance. Some of them deserve special thanks.

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1. Introduction

1.1. Research Background

The science has already provided a sufficient of facts in understanding of how our planet works, which is always advancing. We are now able to see more clearly than ever, how life's intricate complexity is essential for our own survival. Meanwhile, the biodiversity is collapsing, and our climate is changing due to the exponential rise in human pressures on planet Earth, which has now reached the stage where humans now are the primary drivers of change on planet Earth. The science has clarified nine planetary boundaries for human beings to take care of with a clear path ahead to keep the planet within the safe zone, which is comprised of decisive solutions such as re-greening, renewable energy choices, healthy diets etc.

Therefore, the key area of interest of the present world is about the development of these sustainable solutions to protect or enhance the environmental, social, and economic conditions of the present; while the contemporary presence of major global problems of Global Warming and the subsequent Climate change, which is caused primarily due to extensive emission of greenhouse gases such as CO_2. As a country located at the Nordic region in the world, Norway has a closer proximity in preventing the melting down of ice in the Arctic by cooling down the earth.

One of the profoundly affective facts for the climate change all over the world is urbanization with intensification of climate change impacts (Bazrkar, et al., 2015). According to the estimations of UN Population Division (2018), urban population of developed European countries and North America is more than 78% and is expected to increase to 81% by 2050 (United Nations, 2019).

The Norwegian Center for Climate Services (NCCS) suggests that the considerations should be accounted, with projections for changes in climate and hydrology when planning buildings and infrastructure with a lifetime of 30 years or more (1) due to the findings with annual temperature rise by 4.5 ºC, annual precipitation increase by 18%, together with events with heavy and more intense rainfall that will occur more frequently including the flood induced rainfall. The increased intense precipitation has caused instability to the natural handling of Stormwater management from the ground to the node due to excessive water inflow within a short duration.

Subsequently, with the urbanization, the installation of piped drainage systems and increased impervious surfaces at urban scale has caused severe alterations to the natural runoff patterns

(Ress, et al., 2020). The surface runoff volumes have been increased due to the less evaporation, less vegetation, high water use and less infiltration. As well, the increased runoff velocities have been resulted with larger peak flow values in shorter durations (Johannessen, et al., 2018).

Specifically in Norway, the existing stormwater management system is a combined system for gray water, black water and surface water which creates the future/ current risk of overflow if the volume increases due to high and intense rain (KLIMA 2050, 2020). Therefore, the Klima 2050 project promotes to implement a new methodology in developing a new phenomenon for storm water management system in Norway with attractive and moisture resilient buildings. Thus, green roofs match with this idea like a glow and green roofs is suitable as a one feature of the Norway's 3 Step strategy in mapping storm water management (KLIMA 2050, 2020); 1) the infiltration of water from small precipitation events; 2) the delay and detaining of water from medium sized events and 3) safe floodways for the discharge of water from the largest precipitation events. The green roofs are functional in both Step 1 and Step 2.

Sustainability as a concept, is moving forward with the extensive challenges caused by the rapid urbanization. Re-greening the cities as a concept, is a simple, achievable, and a cost-effective solution which is embodied with numerous benefits for the planet's biodiversity, CO_2 sequestration, stabilizing the climate/ global warming, freshwater cycle, and food production process.

Buildings occupies a vital part of zero carbon future and their life cycle amplifies the need of state-of-art solutions to keep the planet within the safe zone, for both new and old buildings as it is not possible to vanish what exists in a blink of an eye. Simply, by the means of sustainability, the Sustainable Architecture is considering producing buildings of today in a state-of-art way without negatively impacting ecosystems and populations in the future.

Green roofs are not only aesthetically pleasing but also unique as a green infrastructure element and it adds beauty to ordinary gray cities. Comparatively green roofs have greater benefits in a single location than other green infrastructure elements in terms of the area efficiency and functionality; specially because of its ability to reduce rainwater runoff in terms of the area efficiency as 30% - 40% of the roof area is covered with roofs and apparently, now it is a worldwide agenda to produce green roofs as a part of the mission to face the current climate challenges and healthier neighborhoods.

Indisputably, adding more green roofs to a city is a future alert for innovation in formatting the structure of the cities and when it comes to angular green roofs, it will be a value addition to the product because of the aesthetic architectural qualities over ordinary flat roof and it creates more blending with the surrounding green nature in Norway. Even though, the green roof concept is not something new to Norway in the history until the 19th century with Sod Roofs in buildings, it has become into a forgotten feature in present day Norwegian commercial buildings and in residential buildings. However, recent interest on green roofs has been subjected to further research as a stormwater management in small catchments or as a method of developing moisture resilient buildings and climate exposure under Klima 2050 projects in Norway (KLIMA 2050, 2020); but not in terms of direct CO_2 absorption or biodiversity perception.

Therefore, now is the time to transform thousands of traditional roof surfaces to green roofs which is an attractive way to bring back the ‘Nature’ to the modern gray cities, in a time like ‘Now’, altering the direction where we travelled so far as human beings to transform our direction into a rebuilding. Extensive green roofs are merely a feasible option both for retrofitting and new developments in an attractive way while managing the stormwater and climate change. Similarly, the green roof production possesses the potential of growing as a new industry to support the future economy in a circular way.

1.2. Hypothesis

The effectiveness of Angular Green Roofs is greater than ordinary flat Green Roofs.

The above hypothesis was set to be the core of the research, by paying attention on the supposition based on limited pre-defined evidence as an initiation for investigation, since there is a subtle reason to change the direction of the current priority given in developing more flat green roofs suggesting its effectiveness in terms of hydrology. Because the angular green roofs hold further benefits with ability to minimize some of the defects and risks found in flat green roofs such as seepage problems (as the rain can be assumed as a vertical force and when applied as perpendicular to the angular surface, the load multiplies by the cosine value of the angle between the vertical and the roof plane; then the infiltration conduction could reduce); when installed as a module on a frame it gives an extra support (to the building form) to high wind loads as well. Parallelly, angular green roofs are architecturally interesting which comprise a broad range of attractive design possibilities.

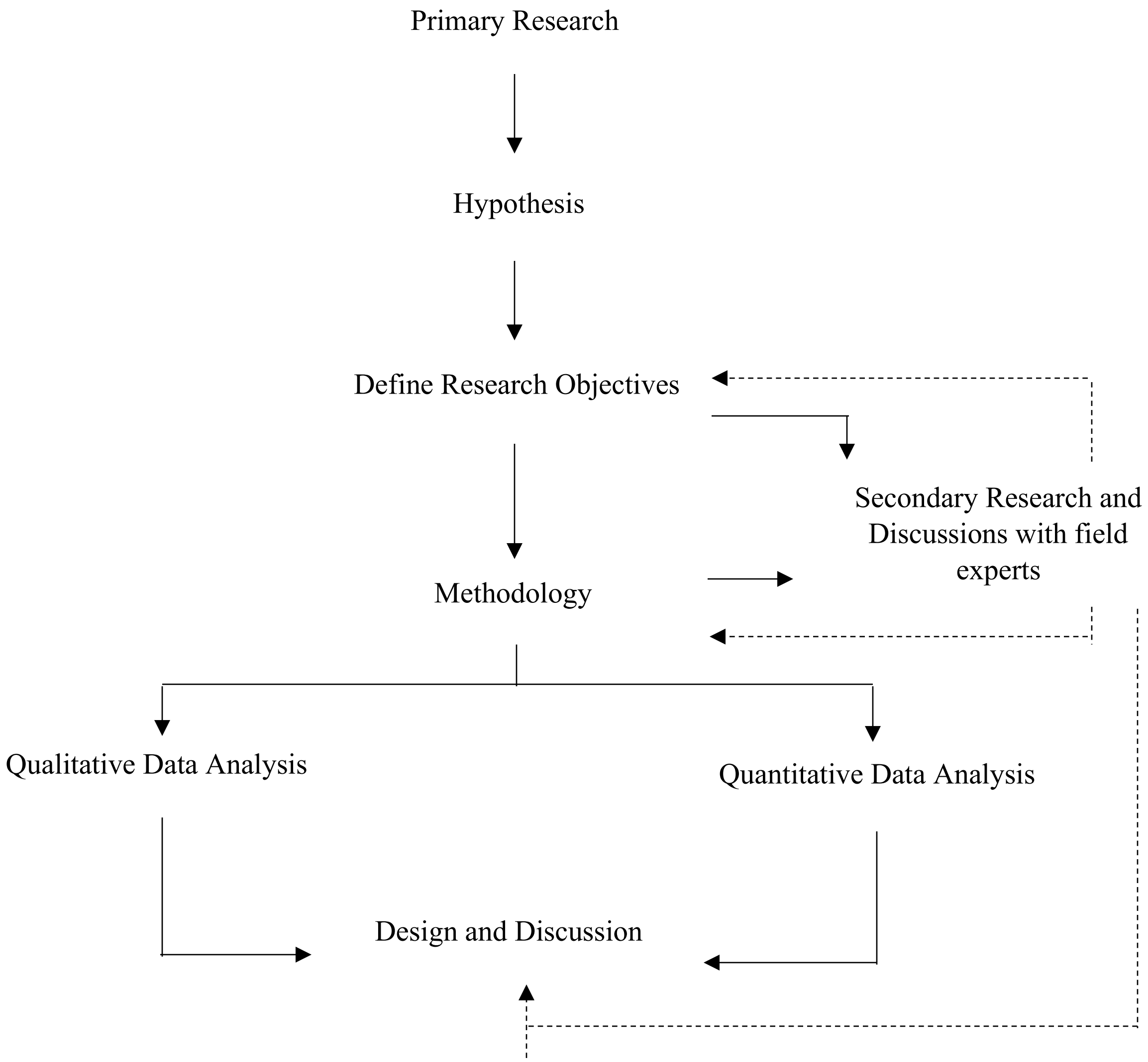
1.3. Aims and Objectives

The main aim of this research is to study and quantify the effectiveness of angular green roofs as a method of climate change risk mitigation in Norway.

The following specific objectives were formulated in order to address the main aim:

1. To investigate the cumulative hydrological performance of extensive green roofs in different locations in Norway as function of local climate and green roof configuration.
2. To investigate the cumulative hydrological performance of extensive green roofs in different locations in Norway as function of green roof configuration and green roof geometry.
3. To investigate the cumulative hydrological performance of extensive green roofs in different locations in Norway as function of local climate and green roof geometry.
4. To quantify the structural effectiveness as the green roof geometry varies.
5. To quantify the CO_2 sequestration of green roof as a function of the roof geometry and building area footprint.
6. To quantify the effect of urban heat island reduction as a function of roof configuration of old office buildings to be retrofitted.

1.4. Research Design and Scope of the work



The study is mainly based on model-based simulations inputs with previously calibrated weather data obtained from Hydrology Department, NTNU. Therewith, calculations based on mathematical equations were used in certain analysis. Some of the analysis were completed in an extensive manner while some other areas were carried out in a limited depth. Additional results were used from secondary research study as well, from the discussions carried out with number of field experts and previous researchers. Eventually, results were analyzed in a broader context connecting to the specific aims and objectives.

1.5. Literature Background

Climate change in Scandinavia has shown a rapid increase in high and intense rain over shorter durations, as well the urbanization has developed more impermeable surfaces causing less infiltration of rainwater; promoting storm water management as an important and a central role in future urban planning (Sjödahl, 2018). The implementation method for Stormwater management in Norway is called 3 – Step Process (Figure: 1), in which green roofs relates into a feature in Step – 1.

Figure 1: *3 - Step Process of Storm Water Management in Norway (Sjödahl, 2018)*

Green Roofs are categorized into two primary forms as Extensive Green Roofs and Intensive Green Roofs differentiated by the Depth of the substrate layer. Generally, while Extensive Green Roofs consist of depths from 150 mm up to 1 m of substrate layer, Intensive Green Roofs consists of the depths less than 150 mm (FLL, 2008). Intensive GR impose high structural loads on building structures and supports a large variety of plants including trees, bushes and shrubs which requires irrigation, fertilization, and high maintenance; often used as rooftop gardens (Johannessen, et al., 2018). Extensive GR impose low structural loads by comparison with Intensive GR, as based on lightweight configuration materials with less material volumes, limiting the selection of plants to the *Crassulaceae* family, herbaceous plants, sedums, and grasses, with low maintenance, nutrients and non-irrigation (FLL 2008; NS 3840 – 2015).

Some GR suppliers suggest a textile retention fabric (Drainage + Storage + Protection) to be used in Angular GR, under the sedum mat, while many large GR suppliers recommend the use of an additional Drainage Layer for flat green roofs (<10% Slope) to ensure efficient drainage facility to the substrate (Figure 2) (Johannessen, et al., 2018).

The widely used type in the Scandinavian countries is Extensive GR with pre-grown vegetation mats (often Sedum Mats) at 30 mm substrate layer (often mixed with additional drainage layer/ separation layers/ detention layers/ protection layers) reinforced with coconut fiber/ Plastic Fiber/ Mineral Wool, considering easy installation process on roofs (Emilsson & Rolf, 2005)

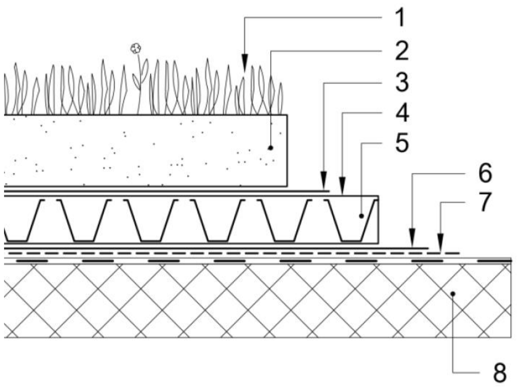
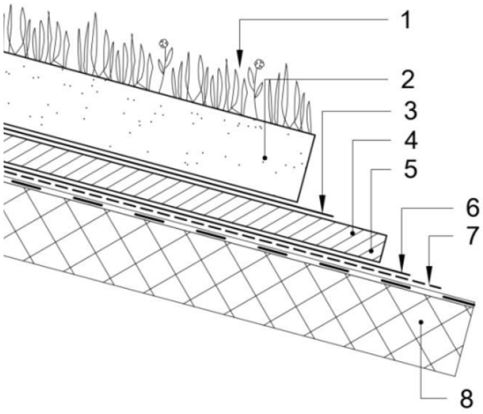
FLAT GREEN ROOF	**ANGULAR GREEN ROOF**
 1 – vegetation; 2 – Substrate (Bulk/ mixed with r/f); 3 – Separation Layer; 4/ 5 – Drainage/ combined detention layer with drainage; 6 – Protection Layer; 7 – Roof resistant layer; 8 – Structural Deck	 1 – vegetation; 2 – Substrate (Bulk/ mixed with r/f); 3 – Separation Layer; 4/ 5 – Drainage layer; 6 – Protection Layer; 7 – Roof resistant layer; 8 – Structural Deck

Figure 2: *Typical configuration for flat and sloped extensive green roofs (Johannessen, et al., 2018)*

The hydrological performance of green roofs is defined by the ability to reduce, delay and attenuate storm water runoff (Johannessen, et al., 2018). The Retention is permanently holding back the water by storing in the substrate layer that can never become runoff and the passive removal of retained water is removed with the Evapotranspiration (evaporation by the plants + transpiration by the soil layer) process on the vegetated soil layer, so that the water is supplied back to the air as water vapor (Zakrisson, 2020). Thus, the evaporation of green roofs helps in cooling down (evaporative cooling) the building surface temperature and outdoor air temperature that can reduce urban heat island effect (EPA, 2021). Hence, the evaporated water amount of the equals to the retained amount of water in soil (Evapotranspiration Volume = Retained Volume).

Green roof detention deals with the runoff water amount that occurs when the precipitation depth exceeds the retention capacity (Zakrisson, 2020), which is a temporary holding back of water resulting in a reduced peak runoff with a prolonged runoff duration (runoff outflow delay) by comparison with a black Roof (Impermeable roof) (Johannessen, et al., 2018). The combined effect of retention and detention is often observed in on-site studies as the mechanism that illustrates in the Figure 3. Thus, detention is greatly effective to prevent the overflow of a combined storm water system in Norway as instead of inflowing all the storm water at once to the storm water line, the water holds back and slowly released, so that the storm water line gets time to reduce or empty the flow before receiving more.

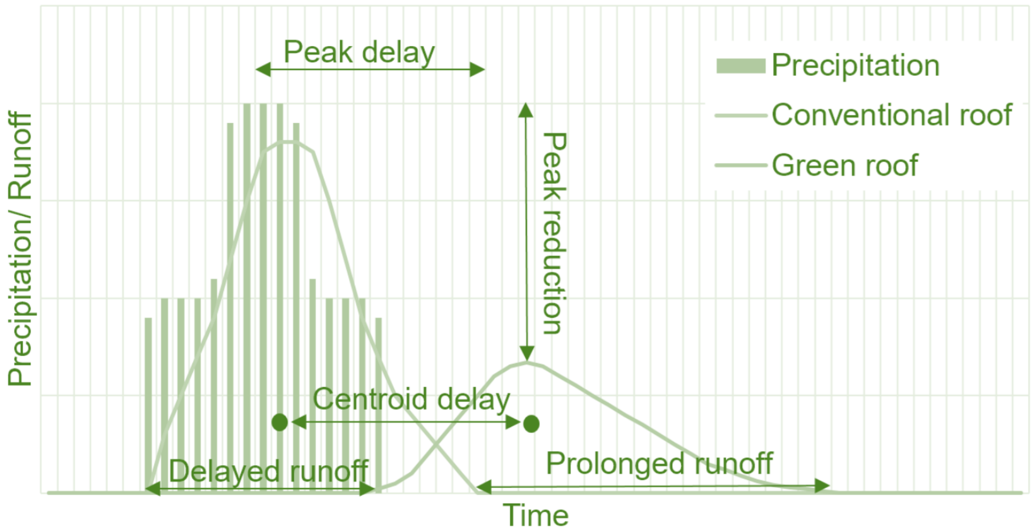


***Figure 3**: Typical Green Roof Runoff Profile (Johannessen, et al., 2018)*

Briggitte (Johannessen, et al., 2018) states that the reported accumulated retention performance in different field studies varies in large differences depending on the green roof configuration, but mostly due to variations in local climate with respect to precipitation and evapotranspiration. Further, she states that “reported accumulated annual retention performance for extensive green roofs in Norwegian and comparable cold and wet climates varying from 27-81%”. Some studies have shown that the increase of the media depth improved water retention and runoff lag time (Johannessen, et al., 2018) (Stovin, et al., 2012) (Soulis, et al., 2017), while others have found that no significant difference effect on retention potential with the increase of the media depth (Buccola & Spolek, 2011). Some studies have found that, the detention performance increases with the increase of the soil depth with prolonged runoff, higher peak attenuation, and longer peak lag times due to longer vertical transport distances in small scale studies (VirginiaStovina, et al., 2012) (VirginiaStovina, et al., 2012) (Johannessen, et al., 2018).

The slope increase has been shown results with rising of peak runoff in extensive green roofs and in drainage layers alone (Stovin, et al., 2015) (Johannessen, et al., 2018) and the peak reduction have been increased as directly proportional to the scale of the green roof (Barontini, 2016). However, comparison of GR detention performance is not easy due to the dynamic nature in internal variations and different performance metrics and calculation methods (Johannessen, et al., 2018); for instance, the flow and peak behavior in different unit times (1 min, 5 min, 10 min) differs to each and also how the events are defined is another affective fact.

(EPA, 2021) states that “One of the most common benefits attributed to green roofs is the reduction in heating and cooling loads in buildings by dissipating heat through evaporation”, as the vegetation can increase the evapotranspiration. There are some studies which shows evidences for the fact that green roofs helps to reduce local air and ambient temperature, not only because of the increased evapotranspiration (U.S. Environmental Protection Agency, 2018) but also caused by the Albedo effect which reflects the solar radiation back to the atmosphere; thus it reduces the earth temperature where high Albedo reflects more and low Albedo reflects less (LiW.C. & YeungK.K.A., 2014). As well, these two scenarios will shift the building’s energy balance as well (U.S. Environmental Protection Agency, 2018). Further it states, “The net effect reduces the temperature of the roof and air directly above it during the day and at night”, and the affective factor for this scenario (Figure 4) includes, latent and sensible heat flux, shortwave and longwave radiation exchange, heat conduction, and thermal storage. Researchers have found that the vegetated roofs consist of significantly higher Albedo than black roofs where the reflectance of a green roof to be 20% while it is 5% for a black roof (LiW.C. & YeungK.K.A., 2014).

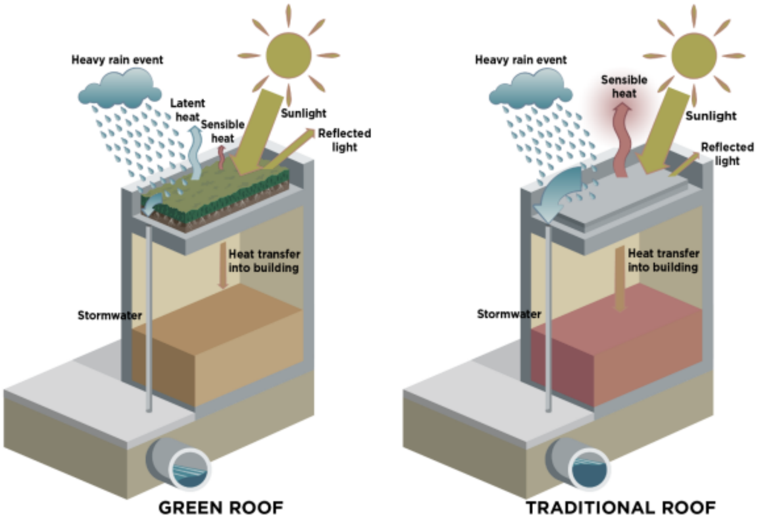


Figure 4: *Heat exchange and water runoff of a GR verses a traditional roof (U.S. Environmental Protection Agency, 2018)*

(Andenæs, 2021) notifies about a particular challenge that associates with green roofs is that the assembling of the green roof is installed directly on the roof surface, which could cause defects to the existing roofing layer which is difficult to discover after the roof has been fully installed due to the need of removal of the covered green roof. This is a time consuming and expensive process which should be provided with sufficient alternative solution such as a module based framed green roof structure. Additionally, over the time leakages would cause seepage issues to through the roof (Andenæs, 2021), that needs to be taken into the account when developing new solutions.

2. Research Methodology

The study has mainly focused on innovating outputs based on the analysis derived through a hypothetical design of a green roof model (module based) to be applied in buildings (mainly large commercial/ office buildings) at universal scale. The main method adopted was running simulations and theory/ equation based calculations as a function of specific actual local climate data and continuous precipitation measurements (from April 2017 – October 2017; an year comprised of unusual high and intense rain events comparatively) at selected locations in different climatic zones in Norway obtained from the Department of Hydrology, NTNU; additionally, the climate data used in energy/ thermodynamics calculations were based on default input values for a similar climate zone as in selected locations in Norway. The outputs obtained from the software, or the tool were manually analyzed by importing to MS Excel in order to customize according to the preference.

As a reference of standards for buildings, SINTEF Building Research Design Guides (“Byggforskserien”) was considered and FLL standards (commonly used in Norwegian Landscape Architecture according to the discussions with field experts) and IBC standards were considered in the hypothetical design/ green roof configuration & geometry and analysis of the results.

Initially, the hydrological simulation was done by using SWMM Version 5.2.0 in order to determine the optimum substrate depth for the extensive green roof to be applied in the comparison of different angular roof. Based on the results (Table 5 & 6), the 140 mm depth was selected for the green roof module. The roofs were also compared with a flat impervious and angular (20^0) impervious roof as well.

2.1. Selection of Locations

The study is based on two different Norwegian locations (Figure 5); Bergen (BER) is a comparatively high and intense raining city consists of steep mountain surroundings located at west coast, hitting around 3110 mm of annual rainfall (Johannessen, et al., 2018), classified as a temperate oceanic climate (Cfb; Köppen–Geiger climate classification); Trondheim (TRD) is located at the mid region of the country closer to the North side, comprised of 1070 mm annual rainfall with cooler Summer temperatures and the rainfall continues as low intense volumes for longer durations, classified as subpolar oceanic climate (Dfc; Köppen–Geiger climate classification).

The locations were selected to represent the sufficiency of application of green roofs for hydrological benefits at a higher interest by choosing densely populated (BER) and averagely populated (TRD) areas with extreme weather conditions (BER) and balanced weather conditions (TRD) within the typical Nordic climates. Comparing TRD with BERG could give a reasonable and acceptable situation to assess the performance for the whole country by this research (South, Mid & North). TRD is influencing as Dfc is the classification which covers most of the area in Norway (Figure 5).

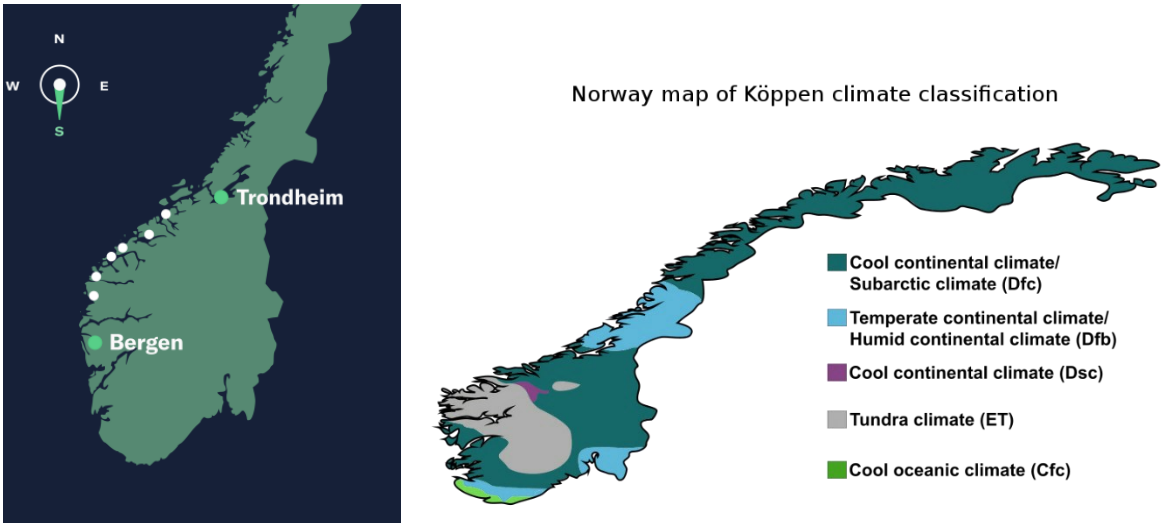


Figure 5: *Norway map of climate classification*

The method of flooding is a cause of increased future precipitation which causes the risk of exceeding design parameters of the existing combined storm water management system in Norway. Therefore, the nature of flood exposure in both cities were also examined (Figure 6) with land slope studies and natural water resources for flood ways, in Google Map. Both Cities has an average slope in the city area around 5^0 while the maximum slope exceeds 25^0 at mountain areas away from the city. Trondheim shows more natural water resources for surface water management by comparison with Bergen (Figure 6) which is an advantage due to more natural detention and also the same fact can become a disadvantage in terms of flood risk by the water resource itself. The mountains are located at closer distance to Trondheim but at considerably longer distances at Bergen, which means that the flood risk due to the topography is higher in Trondheim city due to the short horizontal distance (less water delay) than Bergen city; at the same time, overflowing of

Nidelva River is another potential risk that the Bergen doesn't consist and also the city area in Trondheim (≈ 340 km^2) < the city area in Bergen (≈ 450 km^2) which gives more flood risk to Trondheim due to the reduction of the workable area for land infiltration (assuming the same water table level for both). Even though, it is the case in terms of the Topography, the practical experience differs by causing frequent flooding incidents in Bergen than in Trondheim due to high and intense rain events in Bergen which outweighs the less intense rain events in Trondheim. Therefore, forecasting of the fact that if the flooding in Trondheim could be like is in Bergen, due to future increase of the precipitation in Trondheim. Therefore, comparing these two situations creates a good platform in order to assess future predicted situation (with increased precipitation) to be compared with already existing situation (Flooding in Bergen due to exceedance of design parameters of existing storm water pipe system).

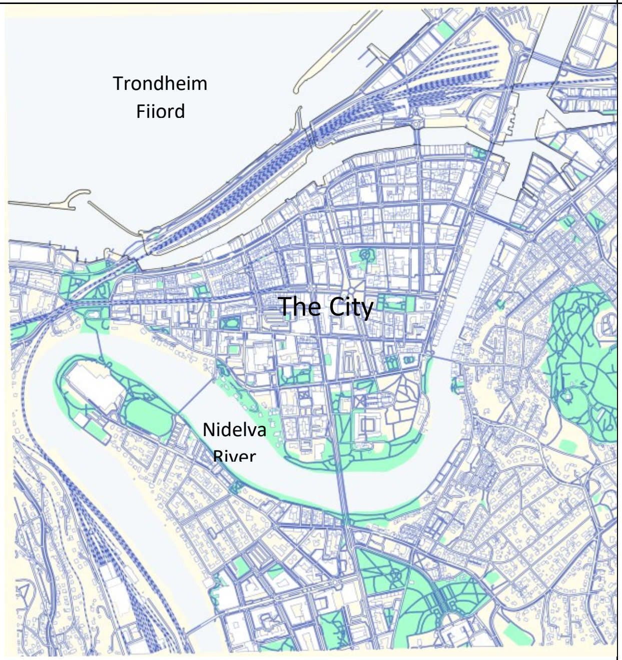
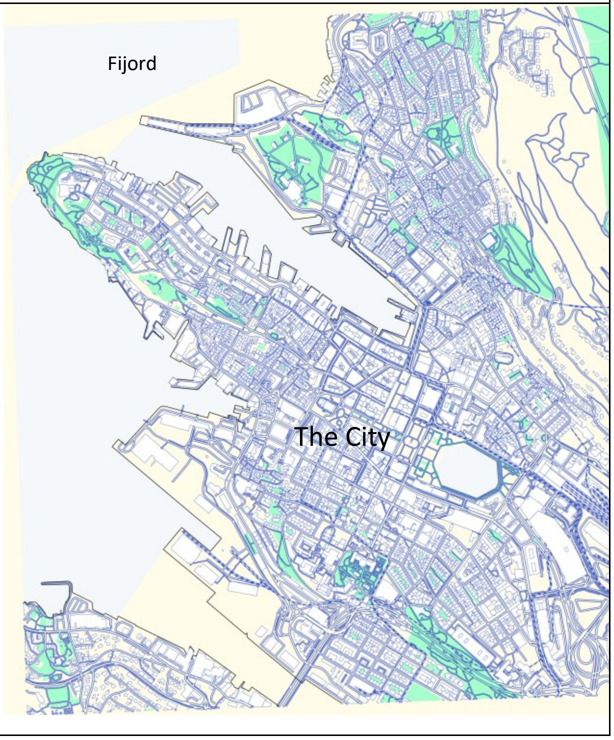
TRONDHEIM	**BERGEN**
	

Figure 6: *City configuration and natural water resources*

2.2. Hypothetical Green Roof Model

Extensive Green Roof was chosen to be applied considering the lower structural load (< 200 kg/m^2), less maintenance and cost effectiveness in retrofitting building roofs compared to Intensive Green Roof systems (BUILDING CENTER, 2022) and it gives the possibility of providing no irrigation and less maintenance. The system was set to be a Modular green roof system installed on a structurally supportive frame as it provides ease of maintenance as not installed on the roof layer and reduce the risk of leakages on to the roof surface which causes seepage issues to the building structure (Andenæs, 2021).

As well, according to FLL Standards (Clouse 5.4.1), ventilated roofs with insulation, should not be loaded with high structural loads as the cooling effect of the roof greening can affect the physical construction of the roof; in terms of the design loads, the FLL standards (Clouse 5.6) recommends decreasing design loads as much as possible which is another reason to reduce the Dead Load by choosing an extensive green roof over an intensive green roof.

Furthermore, transforming a city should happen by step by step which is generally more sustainable than a sudden and huge transformations; extensive GR would be a good option as a start.

According to previous research studies, even though there are ample of studies focused on, on-site testing on small scale GR models, the availability of research focused on larger roof areas is extremely limited. As we observe practically, most of the office buildings or flat roofed buildings located within the city range are placed over larger footprints (Figure 13 & 14); as well, (Johannessen, et al., 2018) mentions that the hydrological peak reduction of the green roof increases with the increase of the GR area. Therefore, a two storied (typical) rectangular office building was chosen, and a hypothetical GR module (Figure 7) was applied on the roof of the building to be used in preliminary simulations. According to (Bengtsson, 2005) (9), directly placed sedum mat on the roof without a drainage layer have been resulted with slower and decreased runoff peaks, over the presence of a gravel drainage layer; therefore, no additional drainage layer has not been placed for the hypothetical model.

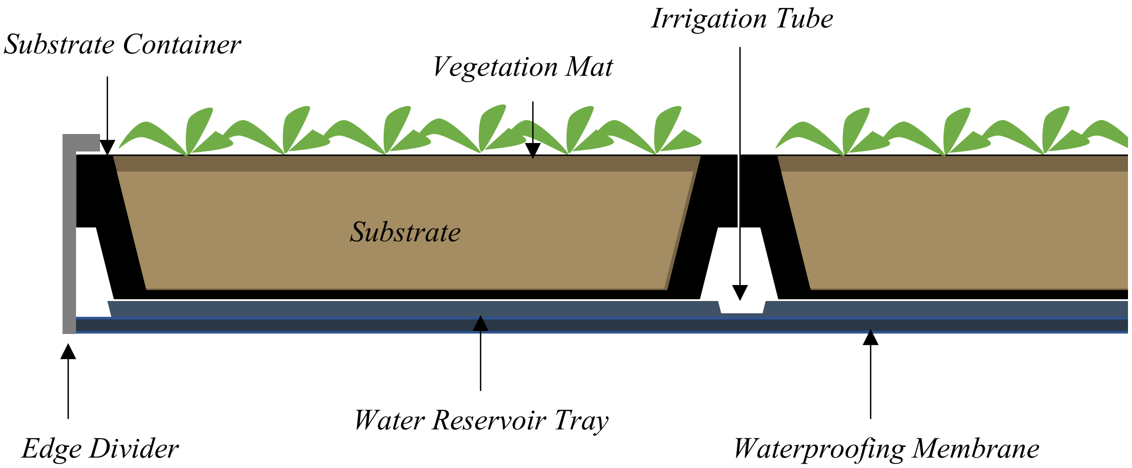


***Figure** 7: Schematic diagram of the hypothetical green roof modular system*

2.2.1. Area Efficiency

Based on the intention of producing a model for a typical large Norwegian commercial/ office building, the average roof area for a typical building in Trondheim was chosen the test area (footprint) to be applied in simulations, which is 340 m^2 (17 m × 20 m). Because, compared with Bergen, Trondheim shows larger roof areas (Figure 13 & 14). Also, the selection of Trondheim was based on the fact that it belongs to the climate classification that covers most of the areas in Norway (Figure 5).

2.2.2. Green Roof Configuration

The primary determinant factor of the detention and retention capacity of the green roof system is the increase of the depth of media (substrate) (Johannessen, et al., 2018). The prolonged runoff, higher peak attenuation and longer peak lag times would cause as the vertical distances increase which results the increase of the detention, while the retention increases as directly proportional to the increase of the soil volume with more depth. Any other parameter that would affect to the increase of the detention and retention is not available to be found. Therefore, the GR was configured to be at different depths as 3 cm, 8 cm, 14 cm; for the analysis, ranging from general minimum to the maximum depth of extensive green roofs (FLL Standards: Clouse 7.2.1 & Table 2).

No additional irrigation was provided and considered as connected to the existing roof drainage path. Berm Height was set to be 10 cm following the FLL standards [(Clouse 6.6.2.1); minimum 5 cm for slope > 5^0 and minimum 10 cm for slope > 10^0], as the hydrological simulation was set to be based on the same for the different roof angles starting from 0^0 to 30^0. Soil to Water ratio was set to be 50% which is the maximum allowable specification in IBC Standards. General recommendation of green roof suppliers is the use of a separate drainage layer for flat roofs (< 10% Slope) to ensure sufficient drainage of the substrate (Johannessen, et al., 2018). As both simulations for flat and angular roofs must be based on equal facts, 10 mm drainage layer was provided for both configurations.

2.2.3. Green Roof Geometry

Paying attention to the hypothesis, simulations were run for different roof angles ranging from minimum to predictable maximum as, $1.4^0 \approx 0^0$ (Flat Roof: TEK 17 minimum slope requirement (1:40/ 3%), 5^0, 10^0, 15^0, 20^0 and 30^0. The range for the roof slope in green roofs ranges from 1^0 to 45^0 (FLL Standards: Clouse 6.5.3.4, Clouse 5.3 and Table 1).

The 30^0 angle was set to be the maximum to be analyzed as it is the general angle specified for sloped green roofs according to the radiation analysis carried out (Appendix A) to assess the co-relationship in between the height increase, radiation increase and the increase of the angle. The angle 30^0 was chosen to set the maximum as the height of the roof increases unbearably after 30^0 (By 115%) which is not a reasonable option when compared with the percentage of radiation increase and also the surface area increase (Table 3) as it causes excessive material volumes which might be challenging to reduce the embodied emissions of the building. Furthermore, number of references and also the recommendations from field experts/ researchers and my supervisor assisted for finding out the common existing roof angles in Norway as, 1.4^0, 7^0, 12^0, 22^0 and 36^0. The average roof angle in Norway was set as 20^0 to be used in simulations/ calculations.

2.3. Capturing of CO_2 Sequestration

The same GR configuration and geometry which has used for Hydrological simulations, were used in estimation of CO_2 sequestration, to be compared with a flat roof vs Average roof angle (20^0) for the locations explained in Section 2.1 (TRD & BERG).

The Plant Type was selected as Sedum - Grass (FLL standards; Clouse 3. 2. 4); the CO_2 absorption rate has taken as 2.5 kg/ m^2/ year (Kuronuma, et al., 2018)(11), assuming no growing time as it is a very fast-growing plant.

2.4. Hydrological Simulations

The model used for simulations follows as Section (2.2, 2.2.1, 2.2.2 and 2. 2. 3) for the locations explained in Section 2.1 (TRD & BERG), for the temperate duration in the year from April to October as explained in the Section 2. The simulation software, SWMM Version 5.2.0 was used in running simulations which is an already in use software by the Department of Hydrology, NTNU, for hydrological analysis in urban stormwater management systems. The comparison of a green roof with an impervious roof (Black Roof) was also done by comparing retention and detention performance in order to justify that how important to produce green roofs for cities. The Retention = Evaporated water volume by Evapotranspiration (Figure 8) and the Detention = Delayed water volume with the Vertical and Horizontal Drainage Distance.

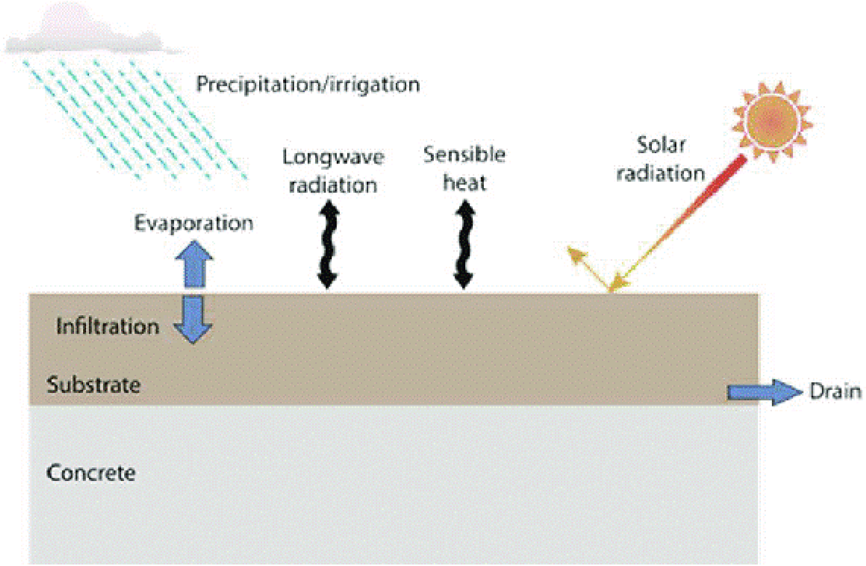
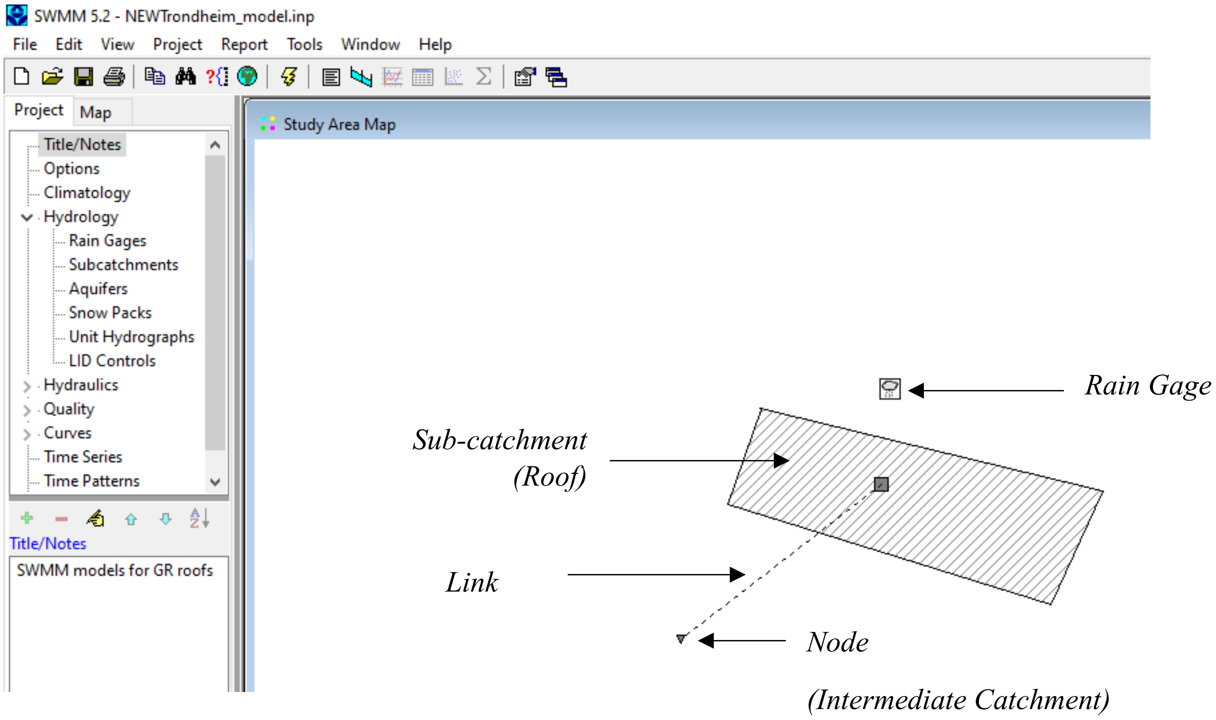


Figure 8: *Green Roof operative mechanism (Sandoval, et al., 2015)*

2.4.1. SWMM Green Roof Module

The Storm Water Management Model: SWMM Version 5.2.0, developed by U. S. Environmental Protection Agency (EPA) was used (Figure 9) in order to run the hydrological simulation by using its LID Control input with a Green Roof Module. The potential of green roof runoff and peak reduction was observed by importing output values (statistical data) to MS Excel and statistically analyzing.



SWMM models for GR roofs

Figure 9: SWMM Software Interface

The optimum depth was selected by observing the summary of results in each GR configuration and for TRD and BERG; for retention of water, produced by the software. The 14 cm depth was selected considering the equivalency of retention capacity and run off co-efficient for each angle. Initial saturation was considered as a Dry Roof (only the moisture content of the soil layer exists which is negligible as 2 mm/m^2).

The results were accumulated after the unit conversion as preferred, (Node – Total Inflow) to produce the Hydro Graph to investigate the flow pattern/ continuity, in order to determine the runoff reduction ability and peak reduction ability for each angle compared with a flat roof and impermeable roof. The runoff coefficients were also obtained from the simulation results to determine the relationship between precipitation and runoff.

The results from the Sub-catchment – Precipitation were imported in order to observe the rainfall behavior. The Flow Duration curve was produced as follows (OSU, 2002 - 2005), to determine the Lag time of the flow with respect to each GR angle compared with flat GR and impervious roof (Flat and average angle of the impervious roof).

- **STEP 1:** Ranked the total inflow for the analysis period of record (from the largest value to the smallest value, involving a total of n values), by using MS Excel Data Analysis option.
- **STEP 2:** Assigned each inflow value a rank (M), starting with 1 for the largest event inflow value.
- **STEP 3:** Calculated the exceedance probability (P) by using the following statistical Equation;
  P = 100 * [M / (n + 1)]; *[P = the probability that a given flow will be equaled or exceeded (% of time), M = the ranked position on the listing, n = the number of rain events for period of record]*
- **STEP 4:** The flow duration curve (Figure 22 & 23) is plotted which is the plot of Flow (roof discharge) vs. Percent of time (Probability of each ranked event × Total number of hours during the analysis period) which shows the plot that a particular Flow (discharge) was equaled or exceeded. Number of hours for the analysis period is 4368 Hours (182 Days × 24 Hours).

The area under the flow duration curve (with arithmetic scales) gives the total flow during the analysis period, and the Median flow is the 50% value.

2.5. Calculations for Structural Performance

Evaluation of Deflection potential of the angular green roof and flat green roof was calculated to determine the effectiveness of the geometry, as the deflection is the structural parameter that affects to the length of structural members (Beams) that supports the Green Roof. This is a critical parameter in retrofitting buildings in order to use existing structural system (to limit demolition of existing or to limit addition of new structural systems), when adding a new extra dead load (self-weight of green roof system).

The forces are assumed to be towards X and Y directions while the beam is inclined and horizontal (Figure 10) and to create a UDL on an inclined beam, the normal and shear force will also be inclined – then the forces in the X and Y direction must be resolved into axial and perpendicular directions to the beam. Hence, the Maximum Bending moment was calculated as follows;

$BM_{MAX} = (w\ L_1\ .\ L_2) / 8$; *where* $L_1 = L$ *(Length of the Beam) &* $L_2 = L \cos\theta$ $(\theta = 20^0$ & $L = 17$ *m)*

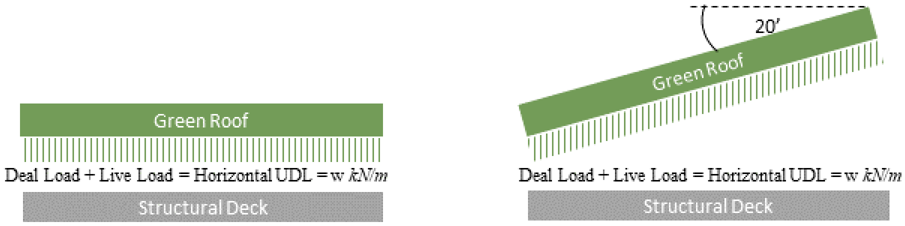


Figure 10: *Green Roof Structural Loading*

The Minimum Dead Load (GR Dry Weight) and the Maximum Dead Load was calculated by using the Green Roof Design Tool (Concept, n.d.).

The GR properties were obtained as follows (Table 1) for the previously selected substrate thickness (14 cm);

Table 1: *Selected Green Roof property Table*

Property	Value
Total Thickness	17.6 cm
Dry Weight	1.3 kN/m^2
Max Dead Load (wet)	2 kN/m^2
Max Retention Storage Volume	40.7 l/m^2
Max Retention Storage Depth	14 cm
Typical Plant Palette	Sedum - Grass

The Bending Moment curve (Figure 29) was produced as a plot of Maximum Bending Moment vs. GR Angle and the deflection reduction (Figure 28) percentages were directly obtained from the curve as it is directly proportional to the BM.

2.6. Calculations in Energy and Thermodynamics

The Green Roof Energy Calculator was used to calculate the amount of energy saved with Green Roof Module with no irrigation, explained in Section 2.2 above, for TRD & BERG, to be compared with an ordinary Black Roof. Separately, the effect of adding irrigation for the energy performance was also calculated for further understanding of the scenario.

The tool has been developed based on the US Department of Energy's Energy Plus software modeling (Green Roofs, n.d.) (Figure 11) and the input values were entered as follows;

Locations were selected as Calgary, CA and Vancouver, CA to be belonged to climate classification Dfc and Cfb to resemble TRD and BERG with a similar default precipitation level for the Summer Season. Type of the building was set to be 'Old Office Building', considering the retrofitting of existing urban buildings to be developed with green roofs, as most of the old buildings are meant to be with high energy demands by comparison with energy efficient modern buildings; according to the references, in 143 Norwegian office buildings, energy consumption ranged from 90 to 520 kWh/m2 (Søgnen, n.d.). Other specifications were entered as following Table 2.

Table 2: *Input Data for the Energy Calculation*

Configuration	Specification
Soil Depth	14 cm
Leaf Area Index	5
Irrigation	No
Green Roof Area/ Percentage	340 m^2/ 100%

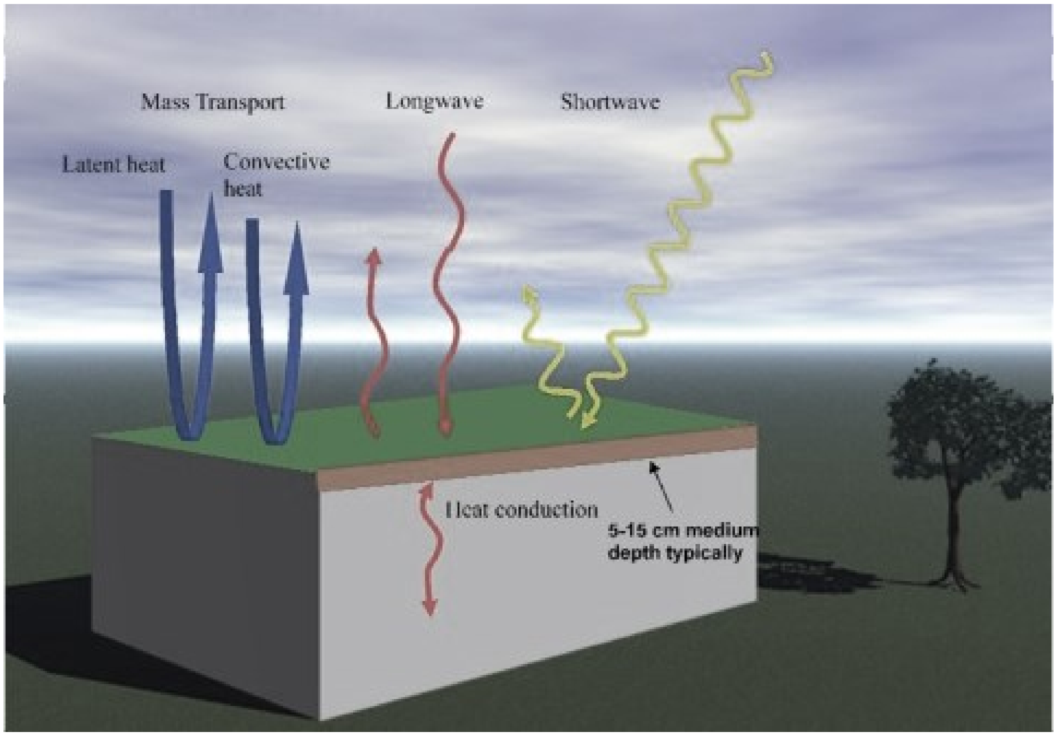


Figure 11: *Surface Energy balance of the roof surface (Gaffin, et al., 2009)*

The green roof module assumes that the convective heat transfer is equal for both green roof and black roof and the changes in heat transfer from green roof are caused by latent heat transfer (Sailor & Bass, 2014) according to the 1st Law of Thermodynamics/ Energy Conservative Theory. The soil characteristics for all green roof simulations have been considered as follows; Thermal Conductivity 0.35 W/mK; Soil Density 1100 kg/m3; Specific Heat Capacity1200 J/kgK; Saturation Volumetric Moisture 0.3; Residual Volumetric moisture 0.01; Initial Volumetric moisture 0.1 (Sailor & Bass, 2014).

3. Results and Calculations

3.1. Precipitation Measurements

Maximum Saturation in the Substrate in 5 minutes;

For the depth of 14 cm with 50% volumetric water ratio = 1× 1×0.14×50% = (0.07 m^3 = 70 liters) = 70 mm/ 5min

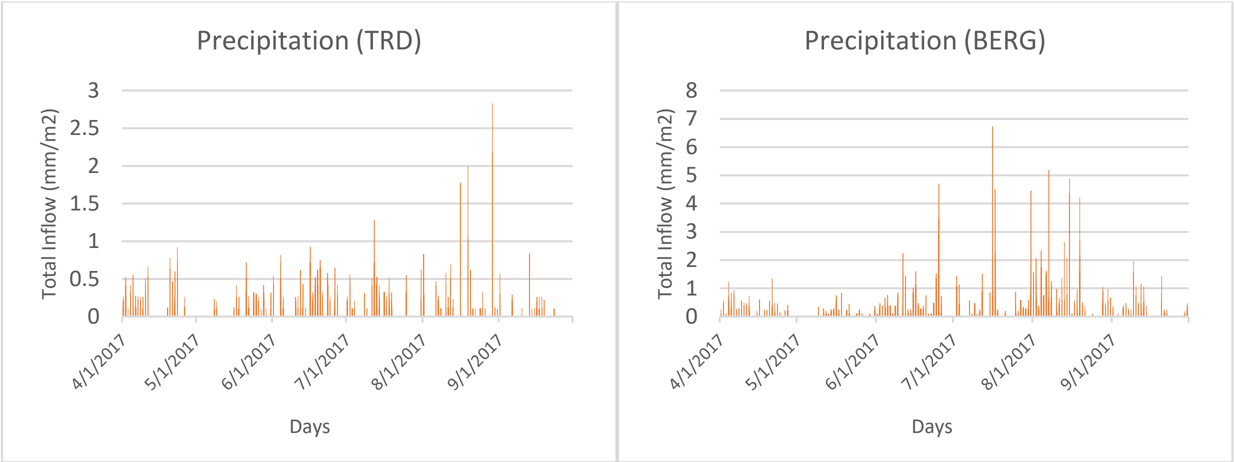


Figure 12: *Temperate Seasonal Precipitation for Trondheim and Bergen*

3.2. Area Efficiency

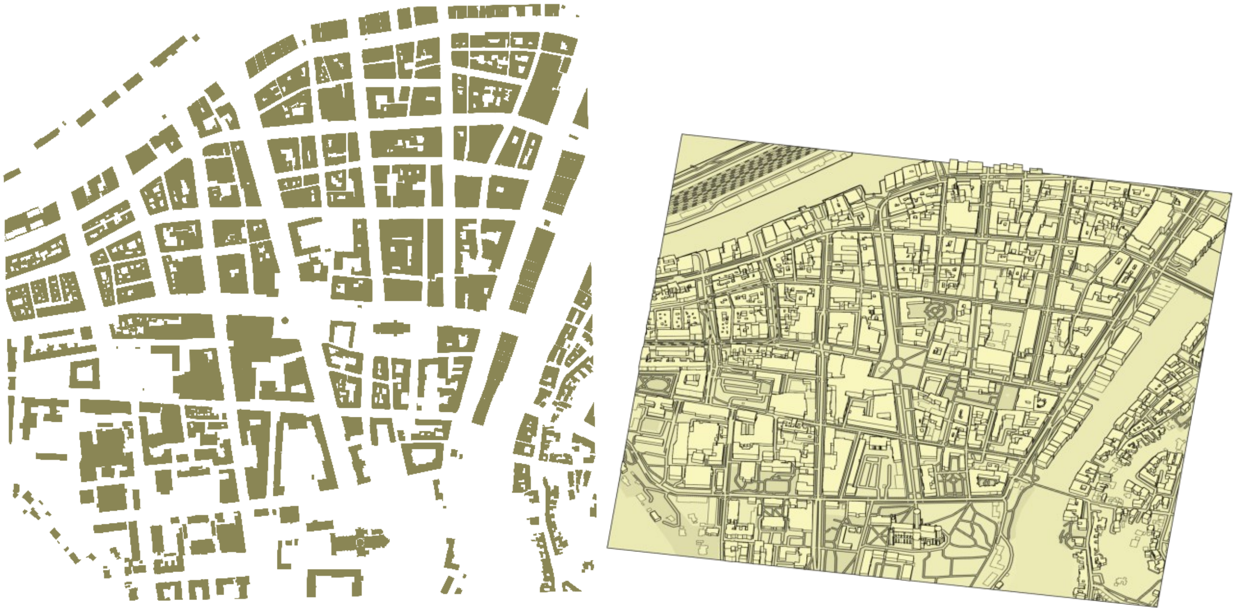


Figure 13: *Building Footprint in Trondheim City*

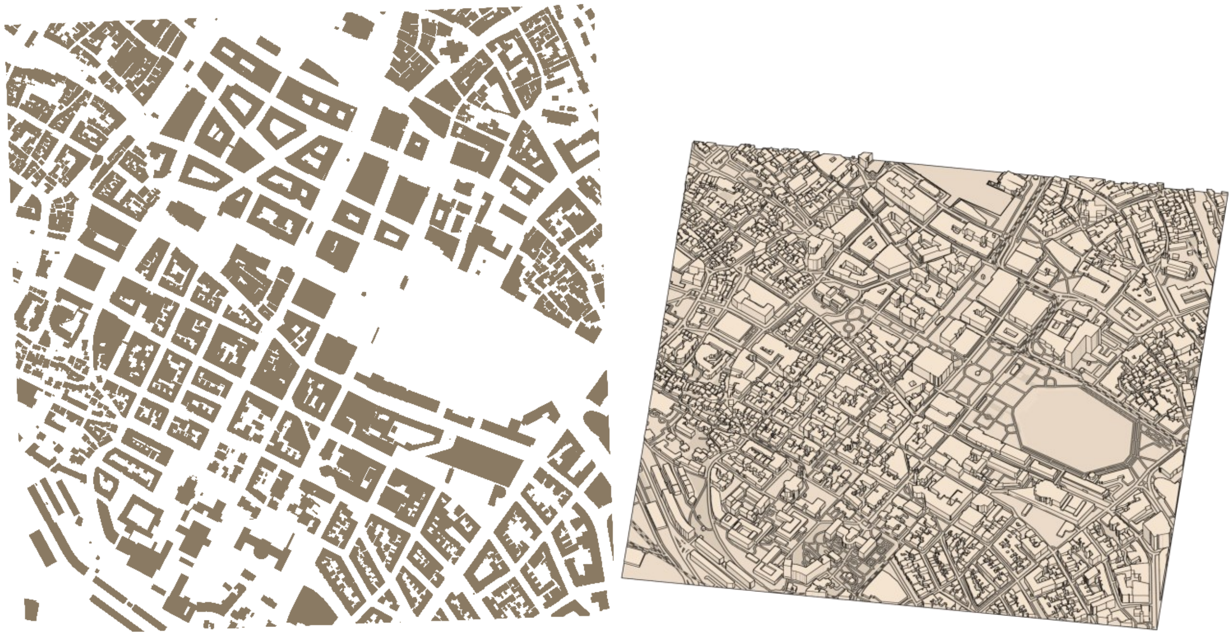


Figure 14: Building Footprint in Trondheim City

Table 3: *Details on Area Distribution*

TRONDHEIM CITY	**BERGEN CITY**
City Area: 1 km^2	
Number of Roof Surfaces = 1153 Gross Roof Area = 355617.13 m^2 Roof Area Footprint = 36% Avg. Roof Area = 345.2 m^2 (340 m^2 = (17×20) m	Number of Roof Surfaces = 1967 Gross Roof Area = 447815.88 m^2 Roof Area Footprint = 45% Avg. Roof Area = 227.6 m^2 (230 m^2 = (11.5×20) m

3.2.1. Analysis of CO_2 Sequestration

CO_2 Sequestration have been assumed as 2.5 kg/ m^2 (Kuronuma, et al., 2018)

Table 4: *Calculation of Annual CO2 Sequestration*

TRONDHEIM CITY	**BERGEN CITY**
Annual CO_2 Sequestration	
For a single building with an Avg. footprint; Flat Roof = 17×20 × 2.5 = 850 kg Angular Roof * = (17/ Cos 20^{RAD})× 20×2.5 ≈ 905 kg For a 1 km^2 Roof Area; Consisting Flat Roofs = 850 kg × 1153 ≈ 1080 ton Consisting Angular Roofs = 905 kg × 1153 ≈ 1200 ton	For a single building with an Avg. footprint; Flat Roof = 11.5×20 × 2.5 = 575 kg Angular Roof * = (11.5/ Cos 20^{RAD})× 20×2.5 ≈ 612 kg For a 1 km^2 Roof Area; Consisting Flat Roofs = 575 kg × 1967 ≈ 1250 ton Consisting Angular Roofs = 612 kg × 1967 ≈ 1400 ton
**Average Roof Angle was assumed as 20^0 considering the rough estimation of data based on the most common existing roof angles (1.4^0, 7^0, 12^0, 22^0, 32^0, 37^0)*	

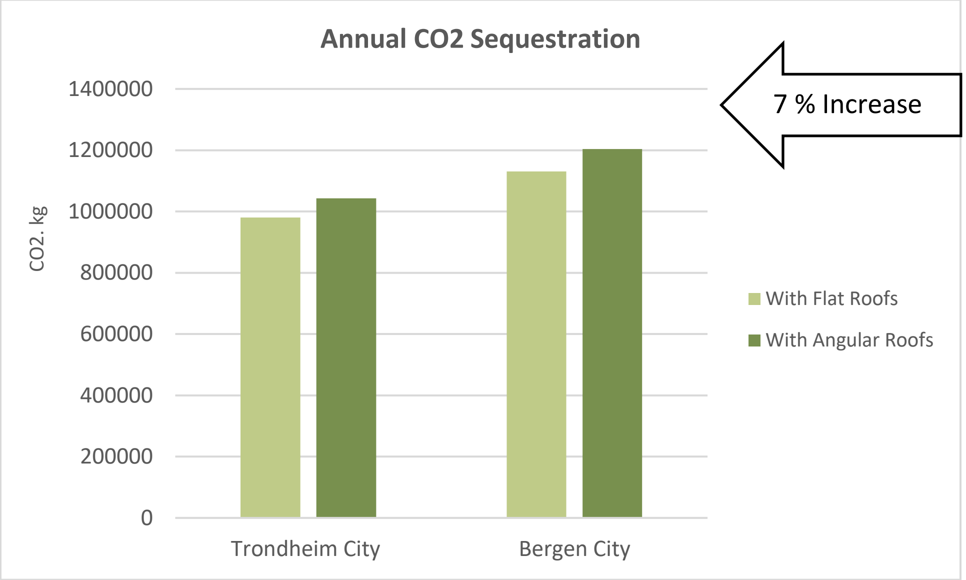


Figure 15: *Potential increase of CO2 Sequestration with Angular and Flat Green Roofs*

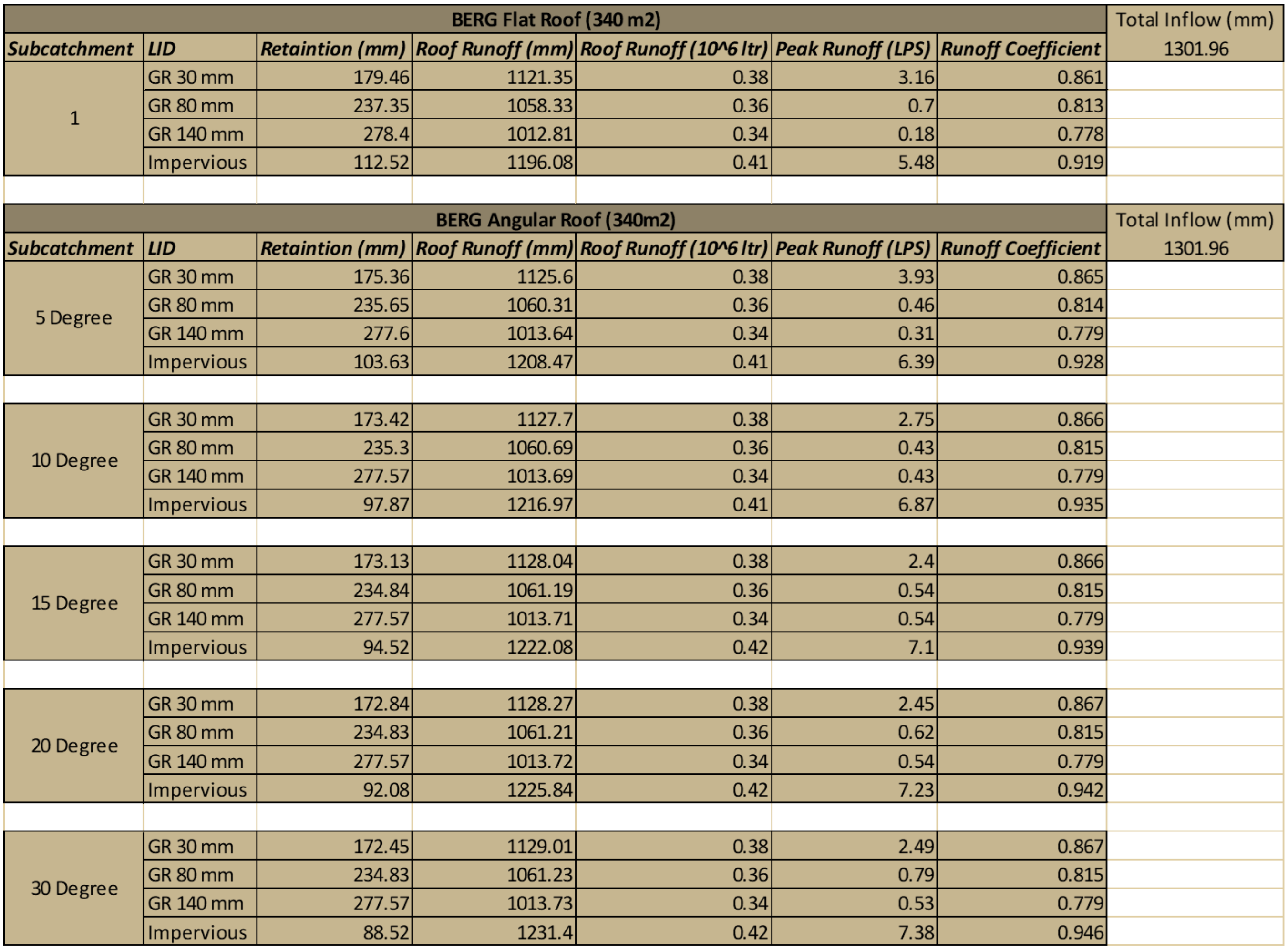
3.3. Hydrological Analysis

Table 5: *Hydrological Performance for different GR configurations and geometries in TRD*

TRD Flat Roof (340 m2)							Total Inflow (mm)
Subcatchment	***LID***	***Retaintion (mm)***	***Roof Runoff (mm)***	***Roof Runoff (10^6 ltr)***	***Peak Runoff (LPS)***	***Runoff Coefficient***	494.04
1	GR 30 mm	103.5	390.69	0.13	0.18	0.791	
	GR 80 mm	155	339.17	0.12	0.18	0.687	
	GR 140 mm	198.1	296.07	0.1	0.15	0.599	
	Impervious	57.85	438.2	0.15	2.1	0.887	

TRD Angular Roof (340 m2)							Total Inflow (mm)
Subcatchment	***LID***	***Retaintion (mm)***	***Roof Runoff (mm)***	***Roof Runoff (10^6 ltr)***	***Peak Runoff (LPS)***	***Runoff Coefficient***	494.04
5 Degree	GR 30 mm	103.09	391.08	0.13	0.31	0.792	
	GR 80 mm	154.97	339.2	0.12	0.29	0.687	
	GR 140 mm	198.1	296.07	0.1	0.15	0.599	
	Impervious	52.44	444.76	0.15	2.35	0.9	
10 Degree	GR 30 mm	103.06	391.11	0.13	0.43	0.792	
	GR 80 mm	154.97	339.2	0.12	0.29	0.687	
	GR 140 mm	198.1	296.07	0.1	0.15	0.599	
	Impervious	49	449.14	0.15	2.45	0.909	
15 Degree	GR 30 mm	103.04	391.13	0.13	0.54	0.792	
	GR 80 mm	154.97	339.2	0.12	0.29	0.687	
	GR 140 mm	198.1	296.07	0.1	0.15	0.599	
	Impervious	47.23	451.74	0.15	2.57	0.914	
20 Degree	GR 30 mm	103.03	391.14	0.13	0.62	0.792	
	GR 80 mm	154.97	339.2	0.12	0.29	0.687	
	GR 140 mm	198.1	296.07	0.1	0.15	0.599	
	Impervious	45.91	453.67	0.15	2.7	0.918	
30 Degree	GR 30 mm	103.03	391.14	0.13	0.79	0.792	
	GR 80 mm	154.97	339.21	0.12	0.29	0.687	
	GR 140 mm	198.1	296.07	0.1	0.15	0.599	
	Impervious	44.01	456.58	0.16	2.85	0.924	

Table 6: *Hydrological Performance for different GR configurations and geometries in BERG*



BERG Flat Roof (340 m2)							Total Inflow (mm)
Subcatchment	***LID***	***Retaintion (mm)***	***Roof Runoff (mm)***	***Roof Runoff (10^6 ltr)***	***Peak Runoff (LPS)***	***Runoff Coefficient***	1301.96
1	GR 30 mm	179.46	1121.35	0.38	3.16	0.861	
	GR 80 mm	237.35	1058.33	0.36	0.7	0.813	
	GR 140 mm	278.4	1012.81	0.34	0.18	0.778	
	Impervious	112.52	1196.08	0.41	5.48	0.919	

BERG Angular Roof (340m2)							Total Inflow (mm)
Subcatchment	***LID***	***Retaintion (mm)***	***Roof Runoff (mm)***	***Roof Runoff (10^6 ltr)***	***Peak Runoff (LPS)***	***Runoff Coefficient***	1301.96
5 Degree	GR 30 mm	175.36	1125.6	0.38	3.93	0.865	
	GR 80 mm	235.65	1060.31	0.36	0.46	0.814	
	GR 140 mm	277.6	1013.64	0.34	0.31	0.779	
	Impervious	103.63	1208.47	0.41	6.39	0.928	
10 Degree	GR 30 mm	173.42	1127.7	0.38	2.75	0.866	
	GR 80 mm	235.3	1060.69	0.36	0.43	0.815	
	GR 140 mm	277.57	1013.69	0.34	0.43	0.779	
	Impervious	97.87	1216.97	0.41	6.87	0.935	
15 Degree	GR 30 mm	173.13	1128.04	0.38	2.4	0.866	
	GR 80 mm	234.84	1061.19	0.36	0.54	0.815	
	GR 140 mm	277.57	1013.71	0.34	0.54	0.779	
	Impervious	94.52	1222.08	0.42	7.1	0.939	
20 Degree	GR 30 mm	172.84	1128.27	0.38	2.45	0.867	
	GR 80 mm	234.83	1061.21	0.36	0.62	0.815	
	GR 140 mm	277.57	1013.72	0.34	0.54	0.779	
	Impervious	92.08	1225.84	0.42	7.23	0.942	
30 Degree	GR 30 mm	172.45	1129.01	0.38	2.49	0.867	
	GR 80 mm	234.83	1061.23	0.36	0.79	0.815	
	GR 140 mm	277.57	1013.73	0.34	0.53	0.779	
	Impervious	88.52	1231.4	0.42	7.38	0.946	

3.3.1. Water Retention

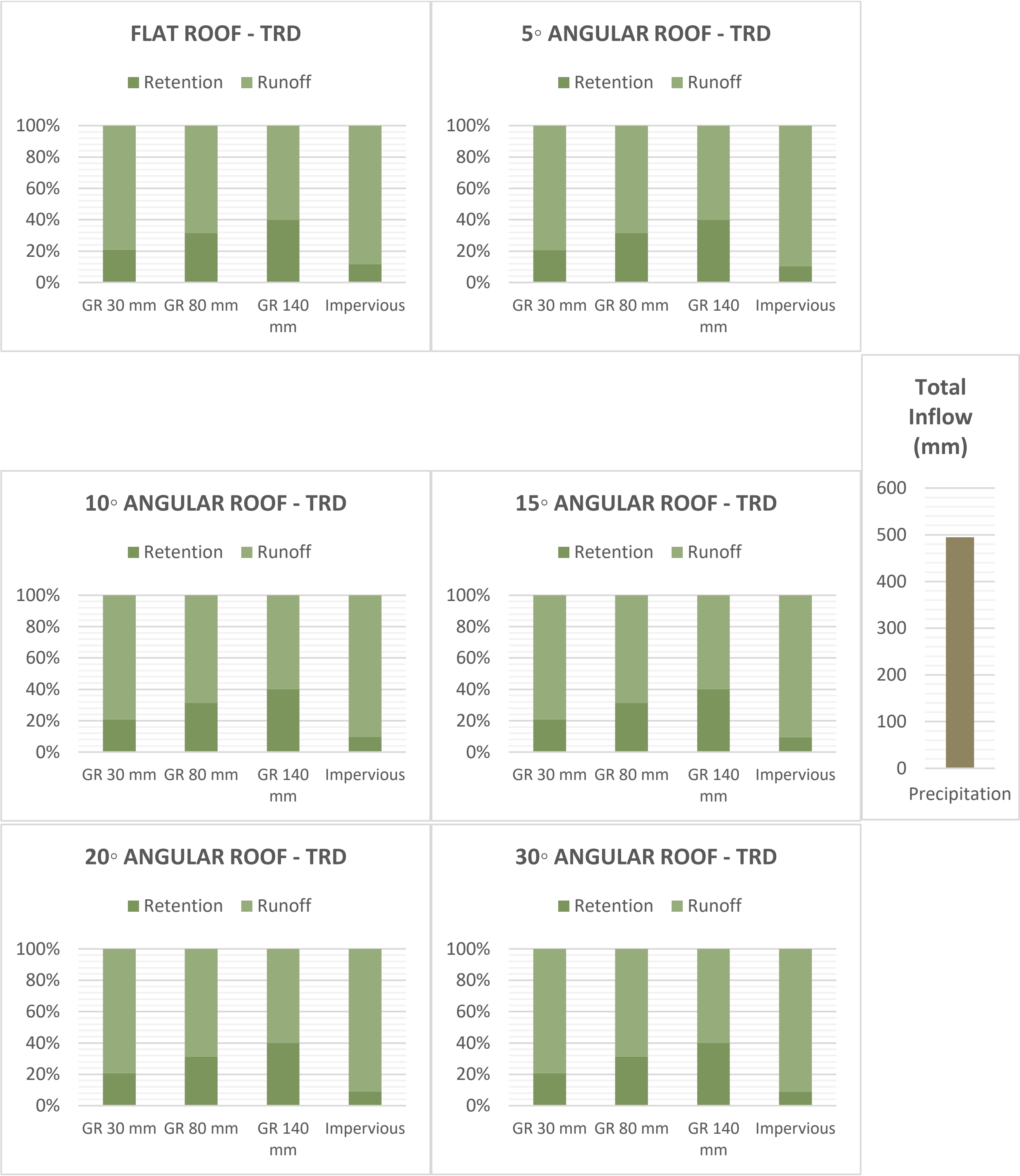


Figure 16: *TRD Seasonal Total Retention from SWMM simulation for 2017 Temperate Season*

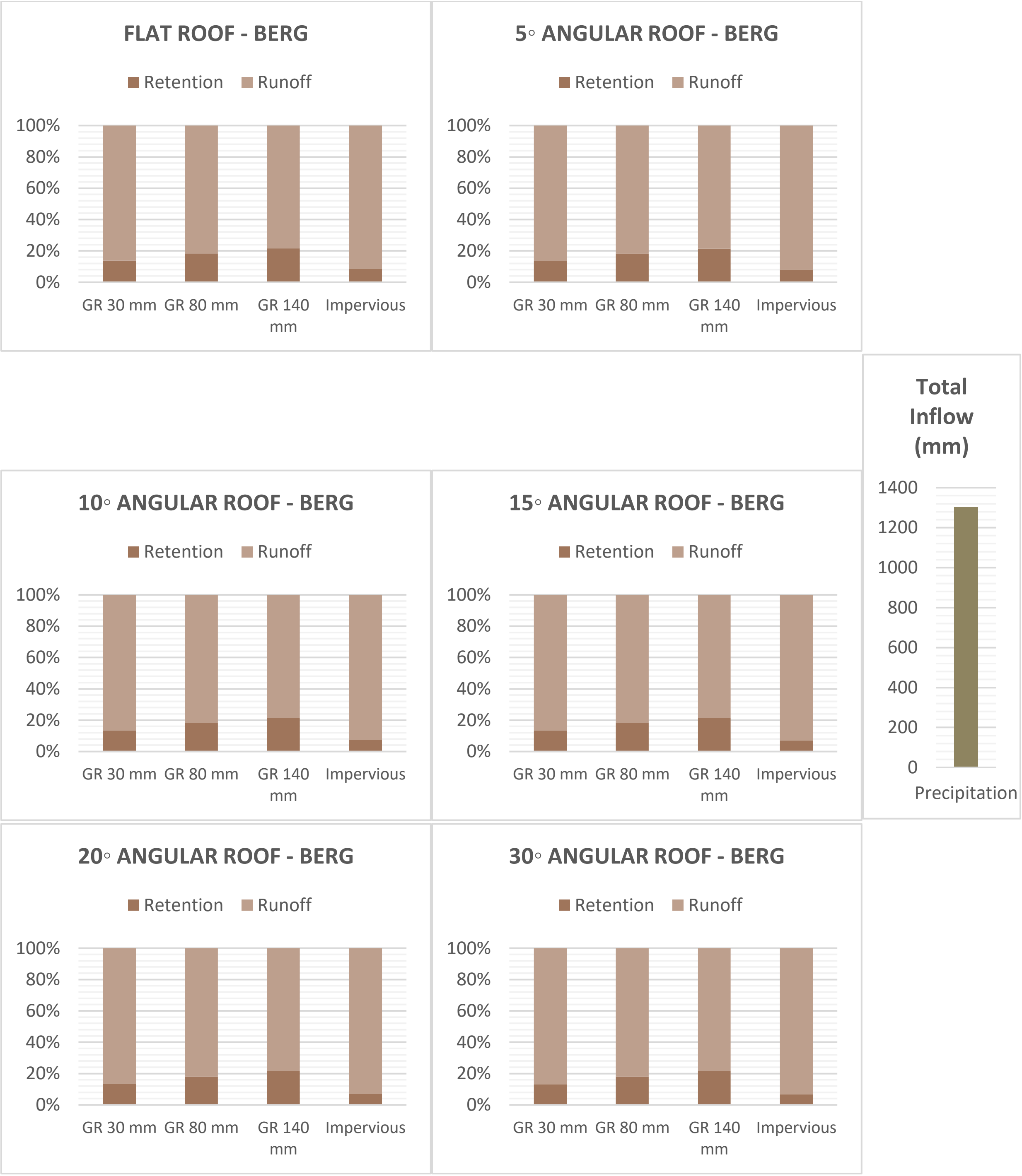


Figure 17: BERG Seasonal Total Retention from SWMM simulation for 2017 Temperate Season

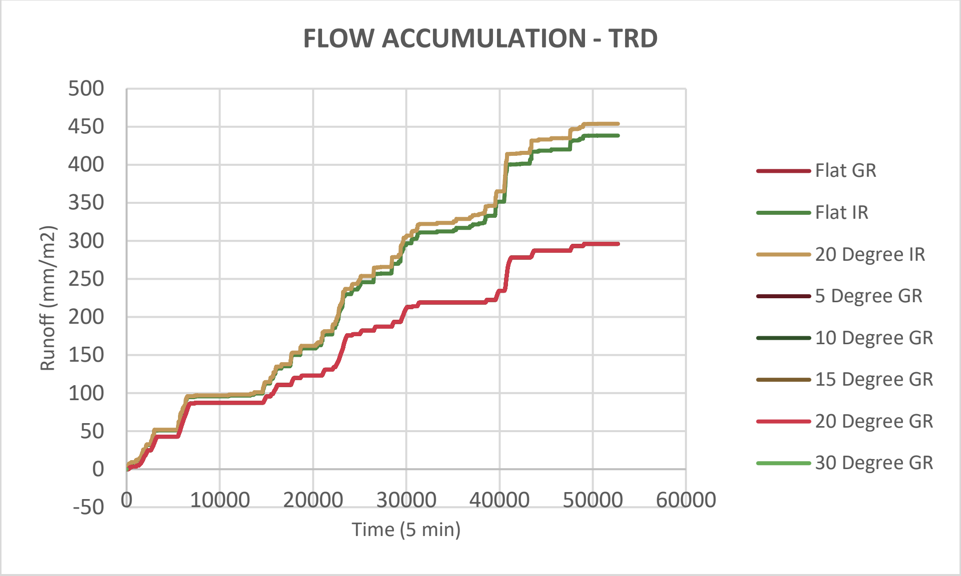


Figure 18: *Flow Accumulation of TRD*

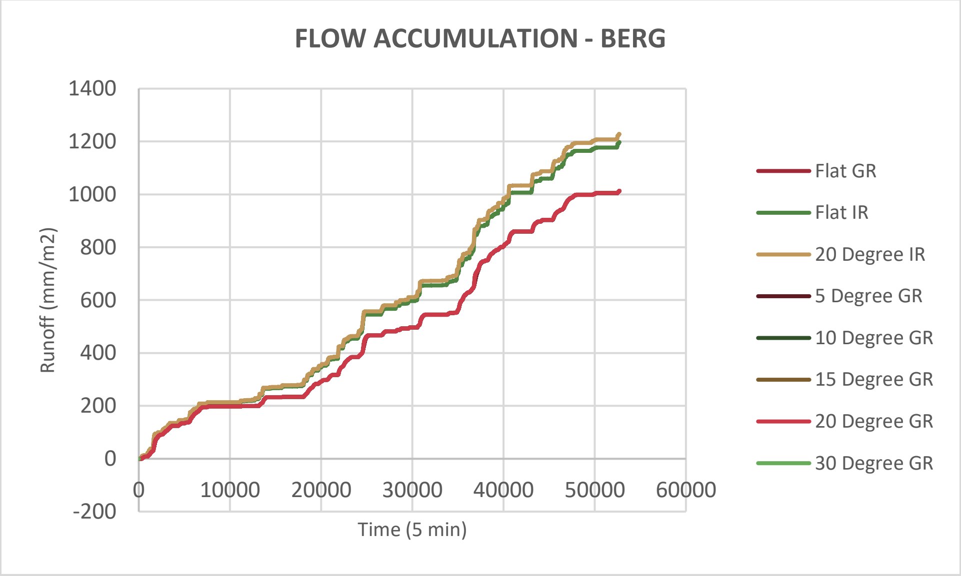


Figure 19: *Flow Accumulation of BERG*

3.3.2. Water Detention

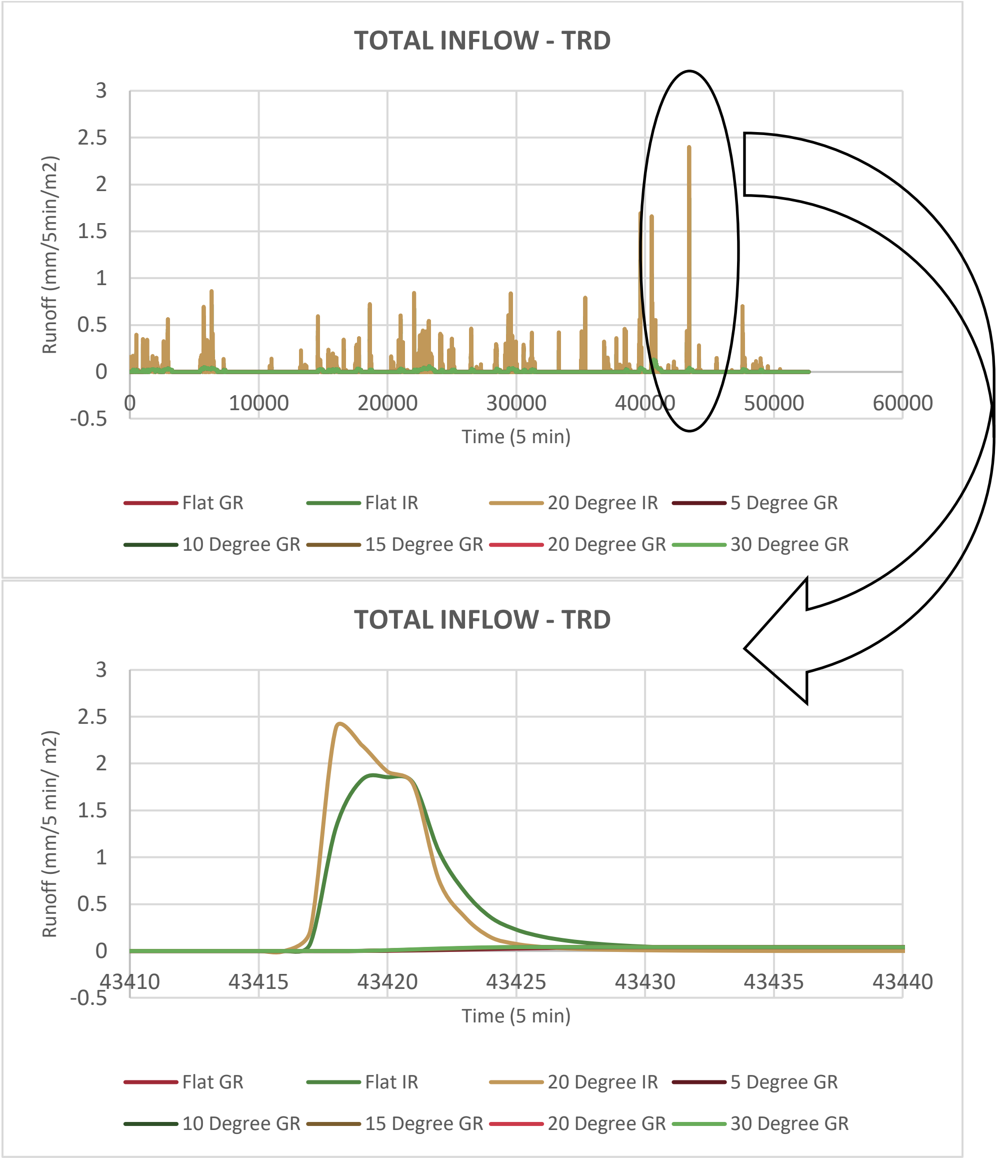


Figure 20: *Hydrological Graph with Peak Reduction and Delay in TRD (2017 April – October)*

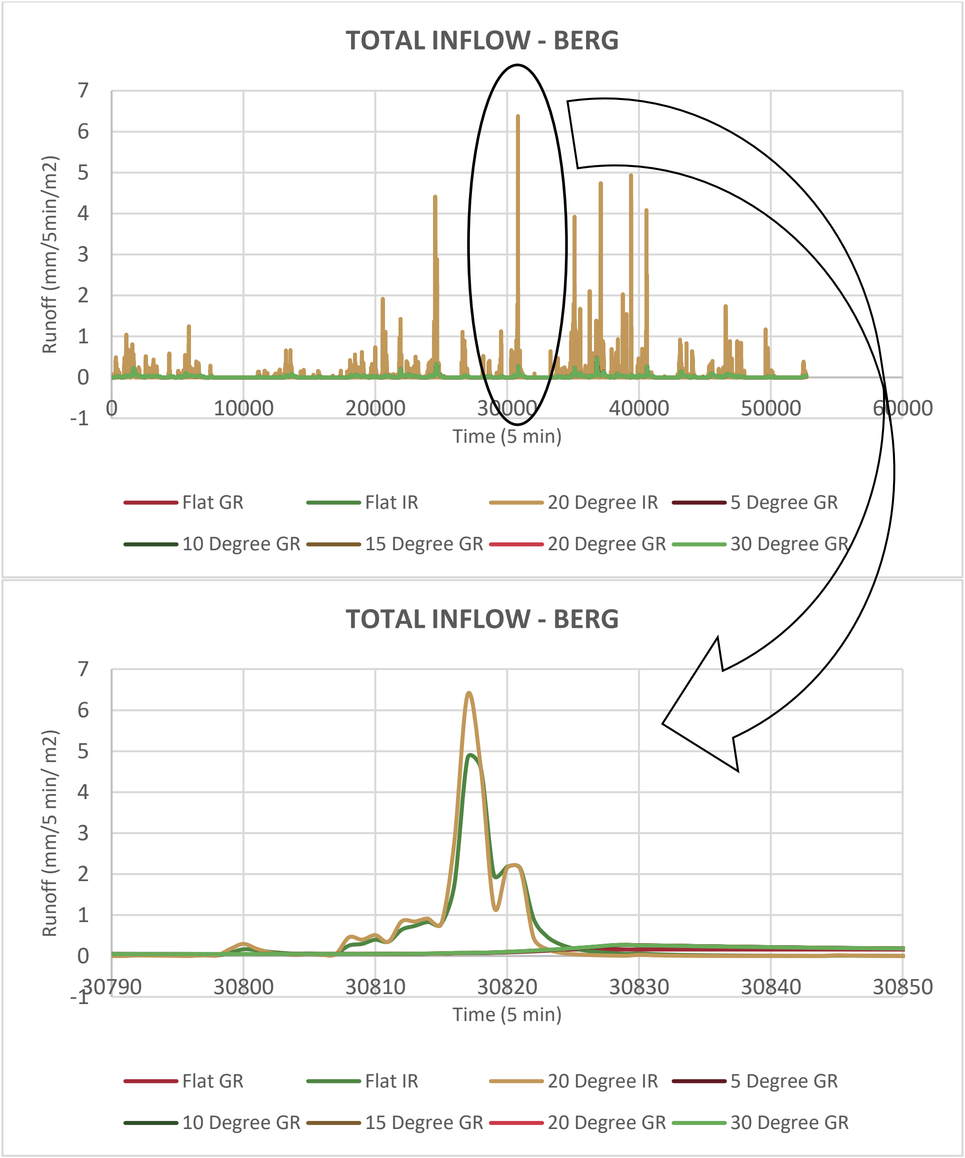


Figure 21: *Hydrological Graph with Peak Reduction and Delay in BERG (2017 April – October)*

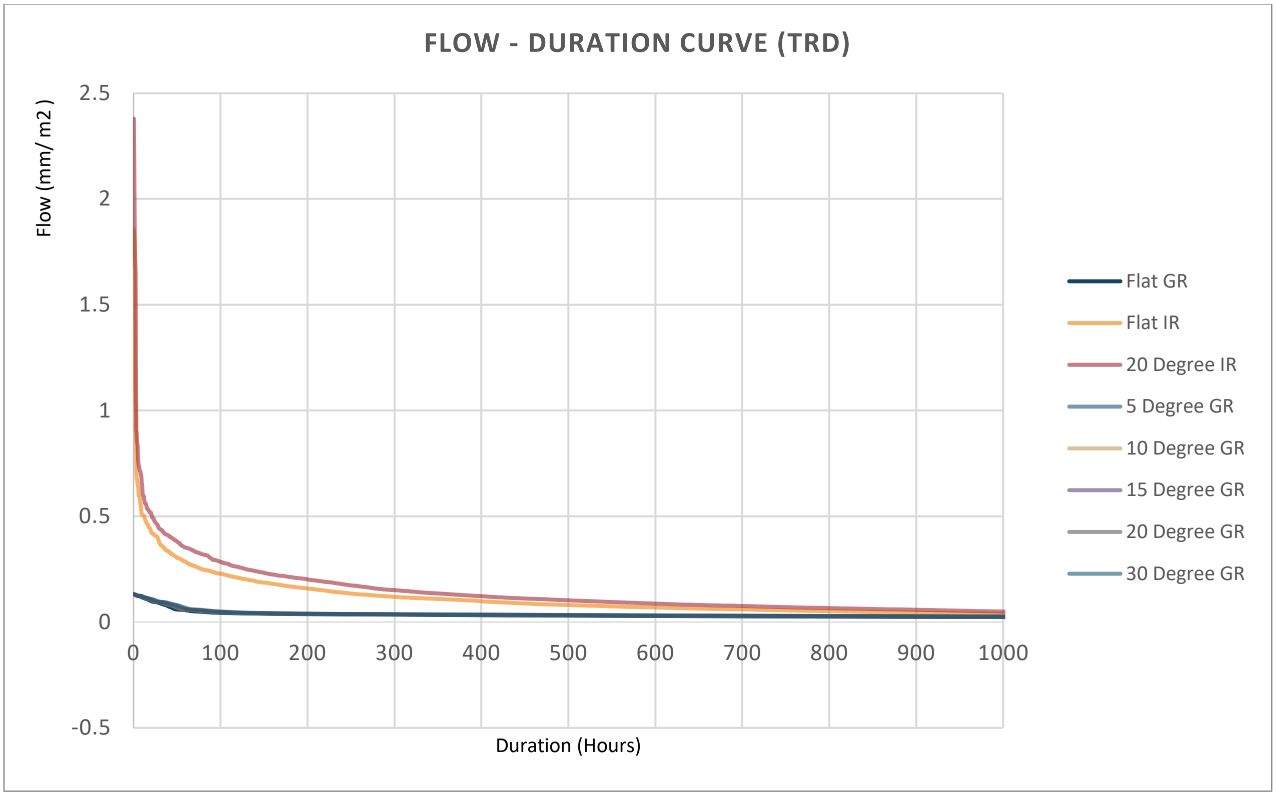


Figure 22: *Flow Duration Curve for TRD*

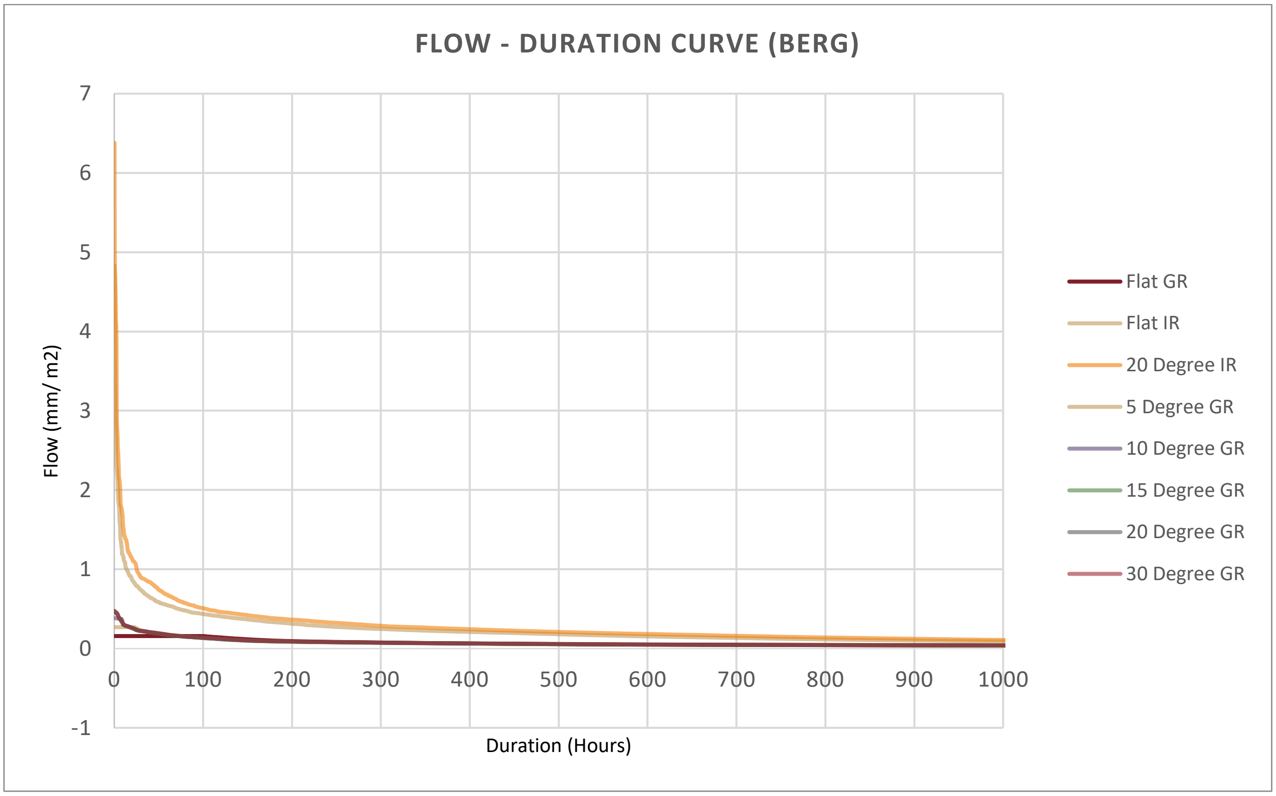


Figure 23: *low Duration Curve for BERG*

3.4. Energy and Thermodynamics

3.4.1. Sensible Heat Flux

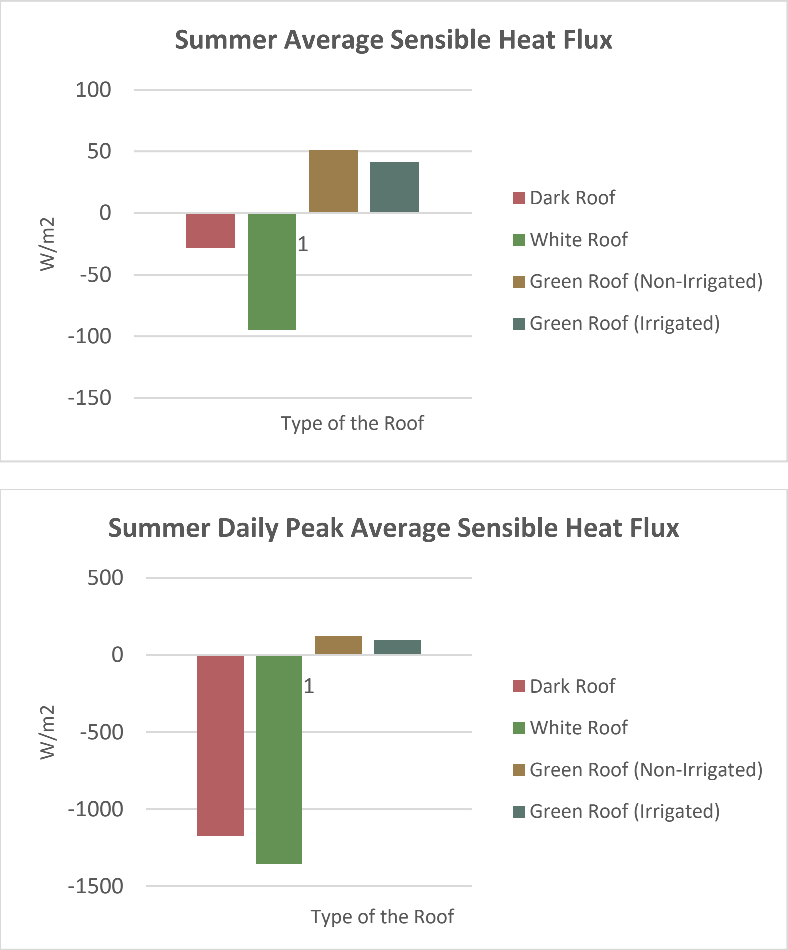
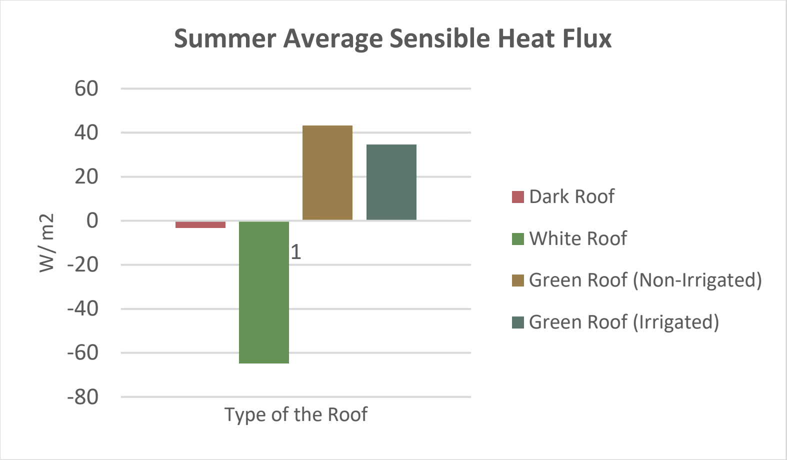


Figure 24: *Sensible Heat Flux - TRD*



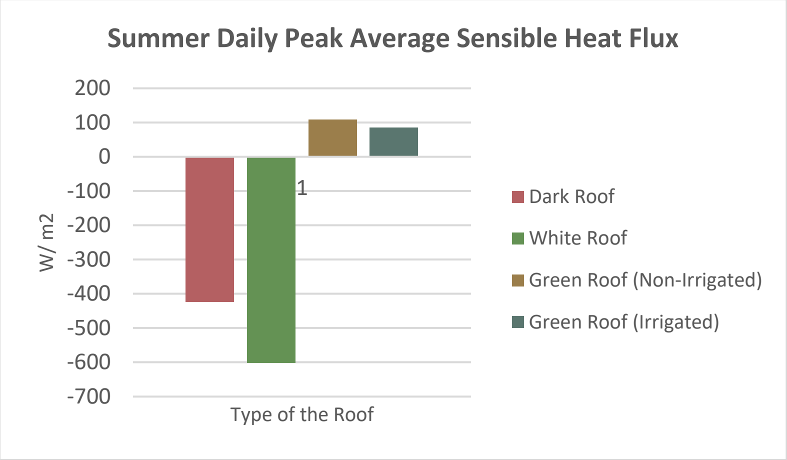


Figure 25: *Sensible Heat Flux - BERG*

3.4.2. Latent Heat Flux

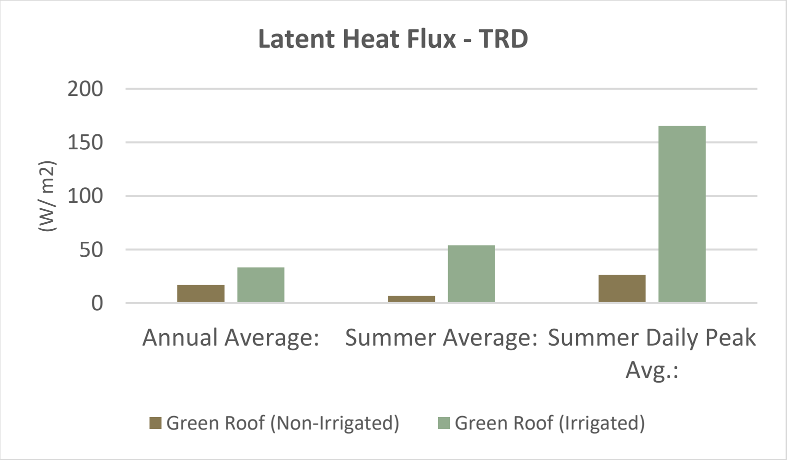


Figure 26: *Sensible Heat Flux - TRD for Irrigated and Non-Irrigated Roof - TRD*

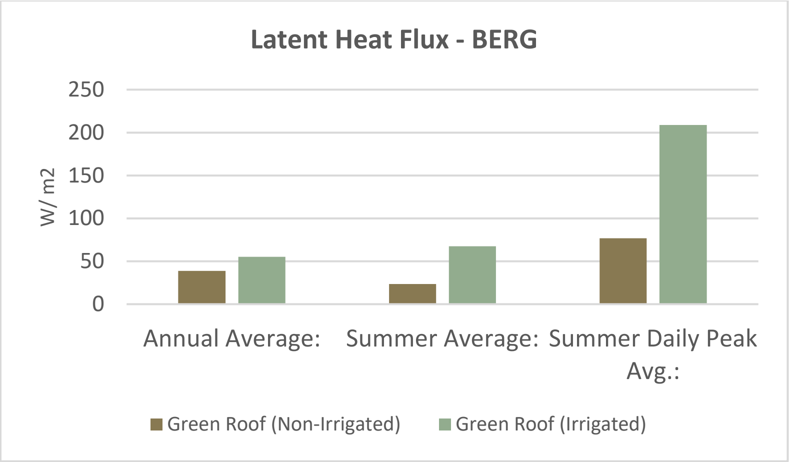


***Figure 27:** Sensible Heat Flux - BERG for Irrigated and Non-Irrigated Roof*

3.5. Structural Performance

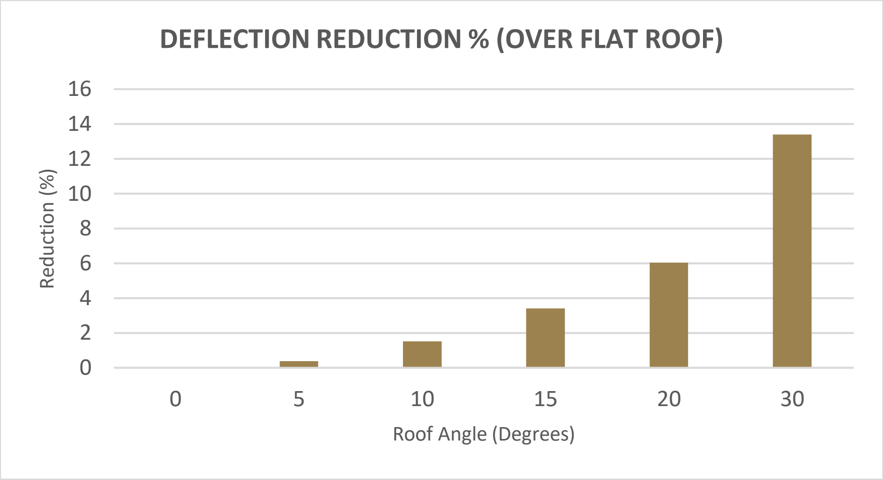


***Figure 28:** Reduction of Deflection as the Angle Increases*

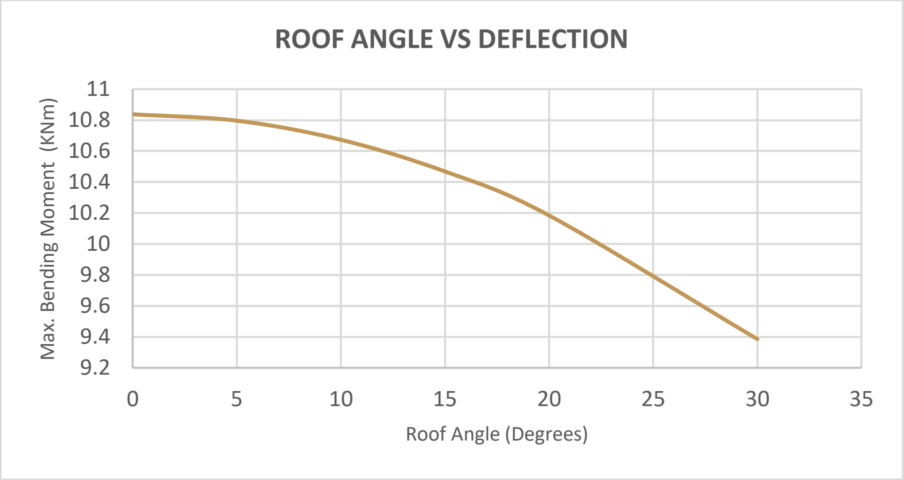
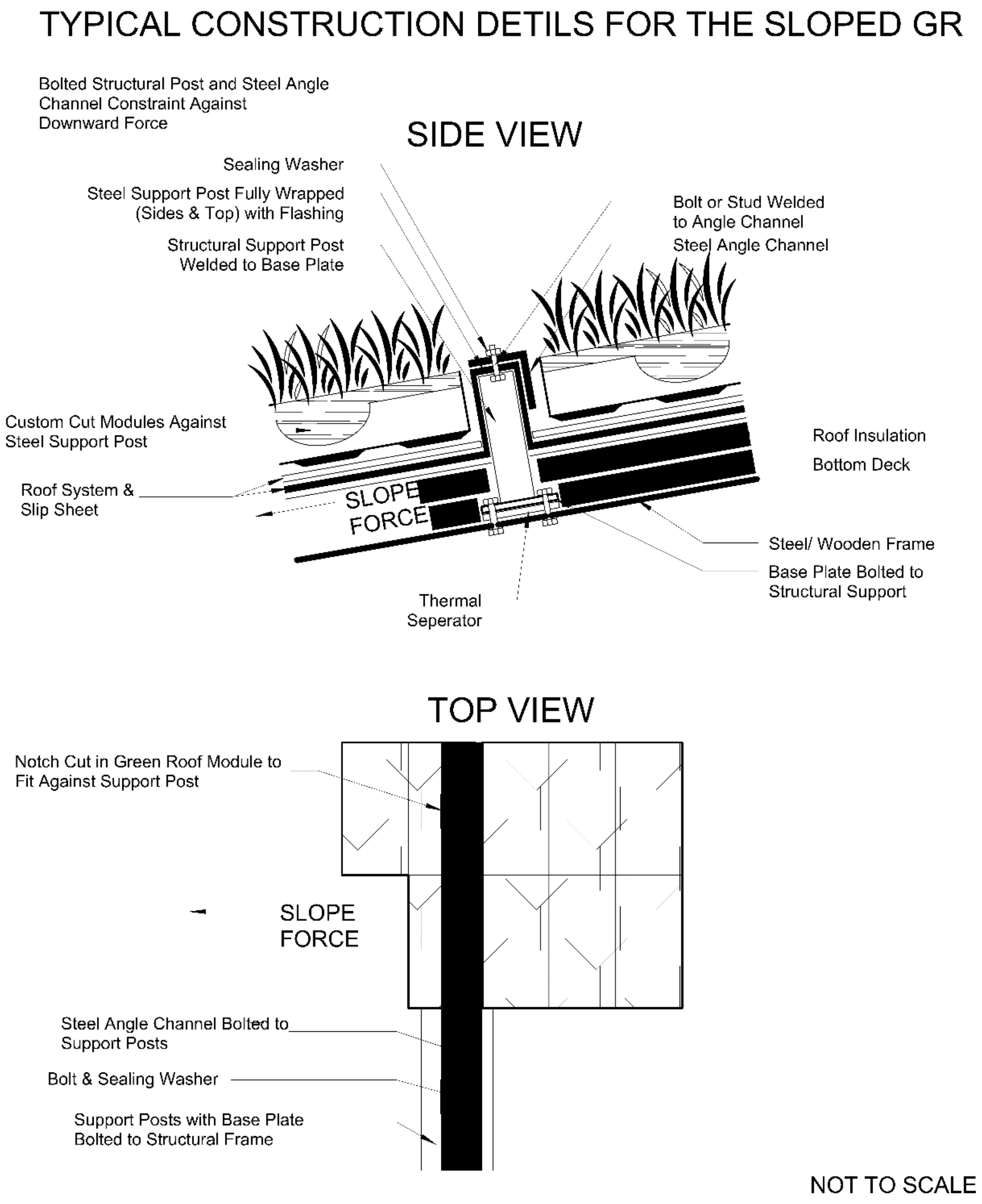


***Figure 29:** Reduction of Max. Bending Moment as the Angle Increase*

3.6. Design and Specifications



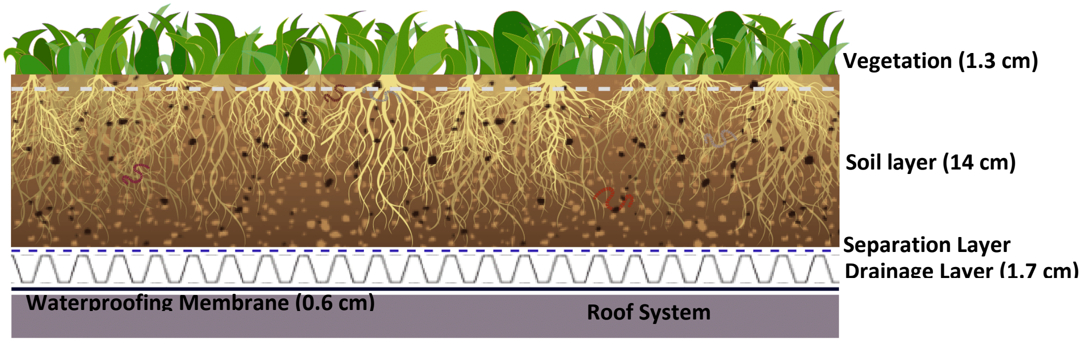


Figure 30: Configuration of the Designed GR

Table 7: Properties and Specifications for the Designed Green Roof

Property	Value
Total Thickness	17.6 cm
Dry Weight	1.3 kN/m2
Max Dead Load (wet)	2 kN/m2
Max Retention Storage Volume	40.7 l/m2
Max Retention Storage Depth	14 cm
Typical Plant Palette	Sedums

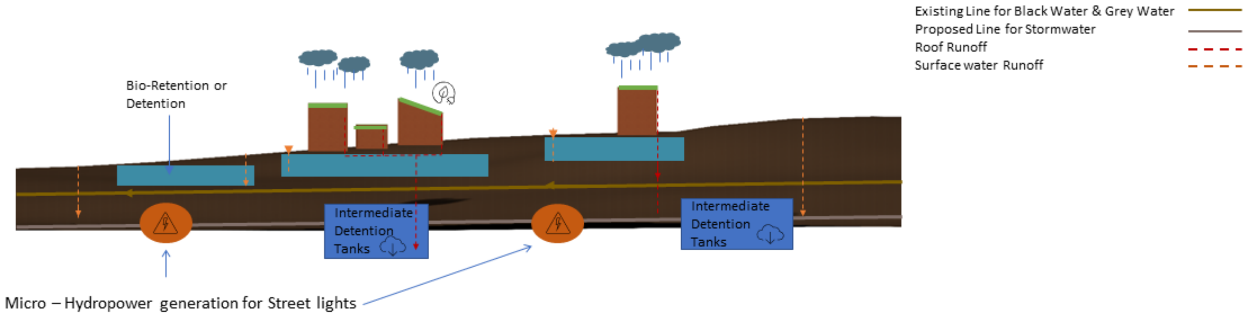


Figure 31: Conceptual Design of the Separated Integrated Stormwater Management System

4. Discussion and Recommendations

4.1. Climate at the Studied Locations

Seasonal total values of precipitation are given in Figure – 12. The longest and highest total precipitation and the highest intensity belongs to Bergen (≈ 1300 mm) while Trondheim (≈ 500 mm) shows a short moderate total with a milder intensity of rainfall. The Peak inflow in Bergen is 60% higher that the Peak inflow in Trondheim and Trondheim shows an evenly distributed rain pattern with significant gaps between rain events, Bergen shows continuous rain events with an unusual distribution. Both cities show its Peak in Fall season. Due to the high intensity/ speed of rain inflow in Bergen limits the ability to Detention than in Trondheim and having considerable gaps between rain events in Trondheim gives the ability to increase its detention capability and as it shows more than 2 days of gaps in most of the rain events in Trondheim, it increases the retention capability as well comparatively with Bergen. Hence, Trondheim doesn't show a significant flood risk in terms of the amount of inflow and Bergen shows a nature of predictable flood risk due to high inflow. Further, Bergen's Peak inflow (≈ 80 mm/ hr) in a day, exceeds the saturation limit of the green roof which is 70 mm. Therefore, the Bergen has a higher tendency to exceed the saturation level of the roof while Trondheim doesn't how any clue like that as its Peak inflow (≈35 mm/ hr) is around 50% less than the saturation level.

4.2. Effectiveness of Hydrological Performance

The results are illustrated in terms of Retention (reduction of total volume) (Figure 16 & 17), Detention (peak reduction/ attenuation and delay of peak flows), for the Temperate Season (2017 April – October); which counts only the liquid rain as an input.

The Table 5 & 6 indicates the differentiation of Retention values, Peak flow reduction and runoff coefficient reduction (runoff as a fraction of precipitation). Observation of the pattern justifies that the retention increases as the substrate depth increases and the difference between an impermeable roof and the 140 mm GR as a fraction, of the precipitation is an increase of a 12% for Bergen and 32% for Trondheim. Thus, it shows that how essential it is to make green roofs in urban cities where impermeable roofs areas occupy around 35% - 45% of the land area (Figure 13, 14 & Table 3). Similarly, even though may references suggest and it is theoretically expected to be low retention (high runoff) as the roof angle increases, the retention volume doesn't show a considerable decrease as the angle increases (Table 5 & 6) in both of TRD and BERG which is a negligible amount as the results suggests; furthermore, the retention value and the runoff coefficient becomes exactly the same for all the angular GR and flat GR at 140 mm or more substrate depth. Therefore, 140 mm depth should be the optimum depth in order to obtain a similar retention performance in any of the angular or flat GR. This scenario must be affected by the direction of the rain load; assuming that the rain is exactly vertical, the vertical distance of a water drop increases as the roof angle increases. Thus, the time lag and a delay of infiltration may cause due to the increase of the vertical distance of infiltration. The negation of the effect of the roof angle can happen due to this behavior which would be the cause to get equal amounts of retention for flat roofs and angular roofs at similar depth after 140 mm. The huge reduction that shows from the retention difference between green roof, impermeable flat roof and impermeable angular roof, further justifies the validity of the result. The runoff coefficient also shows the similar behavior as a function of the green roof configuration and geometry; and for Trondheim, the 140 mm GR, the runoff coefficient indicates C = 0.5; when compared with the FLL standards this value is acceptable; where FLL suggests that the runoff coefficient could be 0.4 (Slope < 15^0) & 0.5 (Slope > 15^0). Even though, Trondheim is acceptable according to the FLL Standards Clouse 7.3.4, the Bergen is C = 0.7, which is a cause due to the high rain intensity in Bergen and not a matter of retention as a fraction of the total precipitation. But the FLL suggest this value for an annual rain event less than that of Bergen, thus C=0.7 makes a plus point for Bergen.

The retention (Figure 16 & 17) in Trondheim is 40% (≈200 mm) while Bergen shows 20% (≈300 mm), for 140 mm depth. These values satisfy the (FLL standards Table 3). The retention is generally a finite measure, therefore, increase of the event sum precipitation gives a decrease of the fraction of water. Comparative analysis is difficult as the raining possess an extremely dynamic behavior, but the retention increases as the substrate depth increases and as the initial moisture content of the green roof decreases. Because when the initial moisture content decreases, the water gets more volume to be retained due to the initial loss and this scenario is affected by the increase of hydraulic conductivity (infiltration) as the initial water content decrease. The obtained result is further justified by the Flow Accumulation curve presented in Figure 18 & 19 for each green roof angle and impermeable roof angle as the reduction percentage is equal to the previous analysis for detention.

The Detention of the green roof causes by the decreased flowing velocities through the drainage layer and substrate depth increase. The Figure 5.A & 5.B illustrates the Peak reduction in both cities for different GR configurations and different geometries by comparison with impermeable roofs. The Peak reduction of green roofs compared to an IR is 92% for TRD and 85% for BERG (Figure 20 & 21), where Bergen shows some less detention potential than that of Trondheim due to increased flowing velocity with high rain intensity. Meanwhile, the peak value of the analysis period has been analyzed and the Peak reduction by a Flat IR is 28% in TRD and 23% in BERG by comparison with a 20^0 Angular IR. Therefore, it shows that adding larger number of green roofs in a city would cause a potential of peak reduction by around 50% when accumulate the integrated systems and the roof angle haven't shown any considerable affect when the GR has a substrate depth larger than 140 mm. The Table 5 & 6 shows that, the Peak Reduction becomes more homogeneous and favorable to the increase of the angle at 80 mm & 140 mm depths, as the increase of the vertical distance for increasing angles is more affective with increased volume and intensity, which causes the reduction of the velocity of water flow to give a slightly higher Peak Reduction to the angular roof than a Flat roof. This scenario depends on the velocity of the rain event, and also the wind speed and wind direction as well. Therefore, the detention performance is a highly dynamic and difficult to picture which has to be further analyzed with increased time series.

However, the peak delay (lag time) doesn't show any quantifiable result in Bergen while Trondheim shows around 15 minutes of a peak delay for Flat IR than 20^0 IR. Generally, application of GR for flat and angular roofs have been resulted with huge reductions in the Peak runoff value compared to a flat or 20^0 IR. The corresponding analysis was carried out for a time series of 5 minutes and for further evaluation in detention, the time series interval can be set to a larger duration such as 10 minutes or 50 minutes. Larger differentiations in Peak reductions can be observed in this manner, as the water volume increases as the analysis time series increases. For further assessment regarding the detention performance, the Flow Duration curve was produced (Figure 22 & 23). The area under the curve is equals to the total flow for 182 Days (≈4000 hours) of analysis period and the Median flow is 50% value. The flow duration curve of Bergen shows around 200 Hours of a lag time for GR (Flow > 0.5 mm/m2/ 5min) than IR while Trondheim shows a lag time of around 500 Hours for GR (Flow > 0.2 mm/m2/5 min) than IR. Both cities show a huge significance of reduction of the GR curve area over IR curve area, so that the total flow reduction.

Compared to the retention, water detention is more affective in sizing of storm water measures at city scale to reduce large amount of inflow within a unit time, to prevent the exceedance of existing design parameters of the city storm water management system to avoid overflow; because detention is the method to delay the peak flows which is an infinite measurement unlike the finite measurement of water retention. Therefore, more than water retention, in terms of addressing extreme future weather conditions, green roofs are not expected to be working out alone to manage macro scale storm water design. The green roofs have a limited ability in entering at every layer at the same time, rather it acts an intermediate layer or the first step (in Norway's 3-step process) to be integrated or to be embedded in a city-scale storm water management system. This study has shown evidence for the significant effectiveness at its unit scale as a function of the local climate and green roof built-up, followed by a theoretical assessment as a basis. In order to assess the combined effect in a linked network of city storm water management system (Figure 31), the green roofs should be connected with number of other LIDs such as bio retention cells connected with intermediate detention basins before reaching safe flood ways. Due to the high volumetric water capacity of such catchment/ detention components, it is required not only to model connected simulations based on theoretical approach, but also to validate the performance with on-site testing with measuring of peak flows per days or hours. This was a limitation in this research due to the practical challenges due to winter climate and time constrains for the master's thesis. Additionally, mixing up the soil layer with light weight organic or plastic fiber such as coconut fiber or mineral wool, would cause not only the reduction of weight but also an improvement of water detention because of the possible flow delay due to the additional friction of the substrate with fiber.

Recent discoveries made by scientists studying the ways in which our planet works are surely of the greatest importance for all of us and the insights are deeply troubling. Nonetheless, they also give us hope because they show us how we can fix things by maintaining planetary boundaries. Therefore, to determine, the effectiveness of hydrological performance alone is not an enough approach in broader perspective. The current architectural practice and technical regulations should be facilitated with integrated solutions. Thus, the studies related to other sub areas were taken into the account in this research.

Moreover, angular roofs may have other types of issues as it is tended to be drying out faster as the radiation increases as the angle increases (Appendix A) which might be a disadvantage in terms of the insulation provided by snow in winter but again the same fact would be a structural advantage as it removes snow from the roof faster than a flat roof due to the sliding load and radiation increase. But the according to the references, the insulation effect of a green roof in winter is around 5%. Another consideration shall be paid for a minor fact as the energy that needs for irrigation might be higher due to the drop.

Eventually, according to the analyzed results in Section 3, the possibility of innovating angular green roofs instead of flat green roofs is a potential option as it doesn't show any disadvantage for hydrological effectiveness but an advantage as aesthetically attractive way to bring back the 'Nature' to the modern gray cities, altering the direction where we have travelled so far as human beings in urban planning to transform our direction into a rebuilding. and easy for maintenance when installed as a framed modular structure. Extensive green roofs are merely a feasible option both for retrofitting and new developments in an attractive way while managing the stormwater and climate change. Similarly, the green roof production possesses the potential of growing as a new industry to support the future economy in a circular way. Thus, the effectiveness in Angular Green Roofs is greater that effectiveness of Flat Green Roofs in terms of endless aspects.

4.3. Effectiveness of CO_2 Sequestration

According to the results presented in this study (Figure 15), the effectiveness in the reduction of atmospheric CO_2 by adding angular green roofs to existing roofs (assuming the structural capacity is adequate or altered) to retrofit and by converting flat roofs as angular green roofs, the CO_2 sequestration by plants and substrates could be increased by 7% of a potential at city scale, mainly due to the surface area increase with angular roofs. It is an adding of around 100 – 200 tons of annual CO_2 to the atmosphere by an average city area. The importance of evaluating this is, as the fact that Norwegian cities consists of higher number of angular roofs over flat roofs but the roof area in most of the flat green roofs are adequately larger. As well, knowing this potential will be a part of reducing the CO_2 payback time in any building in life cycle perspective. As the CO_2 content in the atmosphere is directly proportional to the increase of global temperature, more green roofs in an urban city, where it composed of lack of space for trees must be a promising solution to reduce or reverse global warming by the planetary tipping points.

The limitation which was affected in this quantification is that the inaccessibility to data on existing roof angles in TRD and BERG. Therefore, the data on existing roof angles assumed that the average roof angle in the cities is 20^0. However, it doesn't say any negativity on the idea of transforming the city into green roofs.

One would argue that the angular green roofs increase the material volumes, so that the embodied emissions as the roof areas increases. But the embodied emission for a specific duration is a finite value while the CO2 sequestration is a continuous and auto renewing process over the time and plants are cost effective and natural which would give more plus energy to the building in life cycle perspective.

4.4. Effectiveness of Thermal Performance

Thermal performance of roof surfaces can be defined by surface energy balance based on the energy conservation. References suggests that the solar radiation is the mostly influential factor for the thermal behaviors of the surfaces, then as the radiation increases with angle increase the effectiveness of the angular GR directly proportional. The energy balance is represented by (Net Radiation + Sensible Heat Flux + Latent Heat Flux + Ground Heat Flux = 0); where, sensible heat is the heat that can be sensed by touching the surface and the latent heat is the heat that feel with humidity.

The green roofs increase the evaporative cooling with the presence of water which gives the cooling effect to the surrounding air. In other words, it cools down the outdoor temperature closer to the roof surface in summer. The Figure 26 & 27 shows the average latent heat flux for summer in TRD and BERG. Irrigated roofs have a significantly higher (40 W/m^2/ 80%) latent heat flux as the water availability is higher than non-irrigated GR (dry ground makes latent heat flux low). However, irrigation is not a part of extensive green roofs. The latent heat flux is not applicable for conventional black roofs, as there is no presence of water on black roofs to be evaporated. The high rain exposure in TRD and BERG would be a reason to give operational process of latent heat flux in green roofs.

The sensible heat flux is affected by both of latent heat flux and albedo effect of the surface. This fact causes smaller magnitudes to the green roof sensible heat flux as the latent heat flux is considerably higher in both cities. Green Roofs has a high surface Albedo around 0.4 (fraction of incident radiation reflected by the surface) than a conventional Black roof (Albedo = 0.15), therefore it reflects more radiation waves back to the atmosphere which cools down the roof surface, thus it gives a positive (heat loss from the surface) sensible heat flux value (Figure 24 & 25) for both cities; compared with a conventional black roof in Summer which is advantageous in reducing not building's heating but also cooling down the outdoor air.

The negative values for sensible heat in the conventional dark roof means that the outside air is warmer than the surface which has been differentiated into a cooler outside air with a green roof due evaporative cooling. Then it makes sense to have a higher latent heat flux in summer (Figure 26 & 27) with a green roof than having a dark conventional roof. Consequently, the due to the high latent heat flux, magnitude of the sensible heat flux with a green roof becomes smaller as the energy is conserved [assuming the convective heat (ground heat) is equal in both green roof and conventional roof]. The graphs also suggests that the effect of evaporation is greater than that of sensible heat transfer. Because the radiation reflective ability (represented by sensible heat flux) in the local climate is lower due to the cloud cover and lower sun angle.

The comparison was done only for the summer season in this study as the green roofs are green only in summer. However, winter simulation also should be taken into the account and probably it will reflect more solar waves back to the atmosphere as the albedo is higher in white snow surfaces.

4.5. Effectiveness of Structural Integrity

The references suggests that the durability of an angular roof is greater than that of a flat roof by exceeding its life span by around 25% of time (BSC, 2022), probably a one reason could be that as the load distribution causes less maximum bending moment which leads to less deflection. This can be a motivation for paying interest on producing angular green roofs in retrofitting or in new buildings, as the green roofs causes extra weight on the roof than an ordinary black roof.

The Figure 28 shows that by converting a flat roof into an angular green roof shows a 2% to 8% decrease of the deflection of beams over the deflection of a flat GR, assuming that the beams are simply supported. The calculation was done for the hypothetical modular GR explained in Section 2.2. Generally, a green roof with a 140 mm soil depth would add extra 2 kNm UDL on the supporting Beam when consider the possible Maximum Dead Load (Wet Weight). This weight can be reduced by mixing up with light weight organic or plastic fiber such as coconut fiber or mineral wool, that would cause not only the reduction of weight but also an improvement of water detention because of the possible flow delay due to the additional friction of the substrate with fiber.

5. Conclusion

This research was focused on validating the effectiveness of angular green roofs over flat green roofs and justifying the importance of developing green roofs over conventional black roofs to transform cities as a mitigation of climate change and to use as a storm water management step while making more attractive cities to be blended with nature. Hence, it is possible to prevent and reverse planetary boundaries in the future when people start to think innovatively and not as the way before.

Evaluating the hydrological performance of green roofs to be practiced as a feature in storm water management system in Norway, considering the future risk of increased precipitation levels, was one of the main objectives of the study. The increased precipitation consequently causes exceedance of design parameters of existing combined storm water management system in Norway.

The results were found to be more effective for green roofs as a LID, when applied with mild or moderate precipitations in terms of water retention and detention. The increase of the precipitation has shown decrease of the detention ability while retention which is a finite value decreases as a fraction of the precipitation. Further studies with larger events and longer time series can be recommended to evaluate the detention performance in a more meaningful way. However, green roofs can be more relevant as an integrated layer or the first step, in the stormwater management system in Norway to act as a method of promoting evapotranspiration as a mitigation to reduce urban heat island effect with latent heat flux as it increases with the water presence increases and reducing stormwater flow peaks by around 80% for increased future precipitation compared to a conventional roof. The volume reduction by retaining water in green roofs, as a fraction of the total precipitation, which ranges from 40% to 20% as the precipitation increase from moderate to severe. The retention with green roofs is beneficial in influencing the natural water cycle starts through the evapotranspiration process. Even though it can be expecting to have increased runoff volumes as the angle increases, the angle of the green roof shows no effect for the hydrological performance after exceeding the substrate thickness of 140 mm. Moreover, impermeable roofs show a considerable rise of the peak runoff from around 25% - 30% as the angle increases the green roofs at each angle shows more detention with the slightly reduced peak runoff as the angle increases at 80 mm and 140 mm while 30 mm shows an increase of the peak runoff as the angle increases. Then the detention performance shows a highly affective to the increase of the vertical distance than the affect from the angle which becomes more favorable when the angle increases with increased rain volume and intensity. However, detention is highly dynamic in nature and depends on the rain speed and wind direction and velocity.

The transformation of cities with green roofs have shown a potential of influencing the increase of CO_2 sequestration of dense urban cities with lack of spaces for trees, by around 7% CO_2 sequestration increase with angular green roofs over flat green roofs. This is a cost-effective method that helps in reducing CO_2 payback time in buildings and producing more plus energy over the lifespan of the building. A green roof with a 140 mm substrate thickness has exerted an additional structural load around 2 kNm (UDL) on to a supporting beam which is a critical point to be considered when applying in retrofitting buildings for a city transformation, not only limit existing roof demolition but also to reduce material volumes for new roof constructions. Sloped green roofs has shown a 2% to 8% of reduction of deflection over deflection of a flat roof.

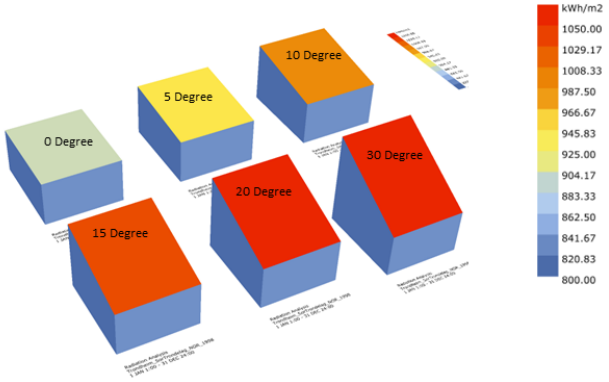
References

1. Andenæs, E., 2021. *Risk assessment of blue-green roofs,* s.l.: s.n.
2. NS 3840 (2015). "Grønne tak. Planlegging , prosjektering, utførelse, skjøtsel og drift. Extensive tak. [Norwegian Standard for extensive green roofs]." Standard Norge, Oslo, Norway.
3. Barontini, S., 2016. Scale dynamics of extensive green roofs: Quantifying the effect of drainage area and rainfall characteristics on observed and modeled green roof hydrologic performance.
4. Bazrkar, M. H. et al., 2015. *Handbook of Climate Change Adaptation.* s.l.:s.n.
5. Bengtsson, L., 2005. *Peak flows from Thin Sedum-Moss Roofs.* s.l.:s.n.
6. BSC, B. S. C. -., 2022. *The Difference Between Flat and Sloped Roofs.* [Online].
7. Buccola, N. & Spolek, G., 2011. A Pilot-Scale Evaluation of Greenroof Runoff Retention, Detention, and Quality.
8. BUILDING CENTER, 2022. *SIG DESIGN TECHNOLOGY.* [Online].
9. Concept, T. P. R., n.d. *Green Roof Retention / Evapotranspiration Modeler v1.0.1.* [Online]
   Available at: https://www.purple-roof.com/model
   [Accessed 18 April 2022].
10. Emilsson, T. & Rolf, K., 2005. Comparison of establishment methods for extensive green roofs.
11. EPA, 2021. *EPA.* [Online]
    Available at: https://www.epa.gov/heatislands/using-green-roofs-reduce-heat-islands
    [Accessed 20 May 2020].
12. FLL, 2008. *Guidelines for Panning, Construction and Maintainance of Green Roofing.* s.l.:s.n.
13. Hao, X., 2010. Water Infrastructure for Sustainable Communities.
14. Gaffin, S. R., Khanbilvardi, R. & Rosenzweig, C., 2009. Development of a Green Roof Environmental Monitoring and Meteorological Network in New York City.
15. Green Roofs, n.d. *Green Roof Energy Calculator.* [Online]
    Available at: https://greenroofs.org/green-roof-energy-calculator
16. Johannessen, B. G., Muthanna, T. M. & Braskerud, B. C., 2018. Detention and Retention Behavior of Four Extensive Green Roofs in Three Nordic Climate Zones.
17. KLIMA 2050, 2020. *Annual Report 2020,* s.l.: s.n.
18. Kuronuma, T. et al., 2018. CO2Payoff of Extensive Green Roofs with DifferentVegetation Species.
19. LiW.C. & YeungK.K.A., 2014. A comprehensive study of green roof performance from environmental perspective.
20. Nations, U., 2019. *World Urbanization Prospects,* s.l.: s.n.

21. NS 3840 (2015). "Grønne tak. Planlegging , prosjektering, utførelse, skjøtsel og drift. Extensive tak. [Norwegian Standard for extensive green roofs]." Standard Norge, Oslo, Norway.
22. OSU, 2002 - 2005. *OSU Origon State University.* [Online]
    Available at: https://streamflow.engr.oregonstate.edu/analysis/flow/index.htm
    [Accessed 15 Apri 2022].
23. Patel. A. S., 2008. Water Management
24. Pazwash. Hormoz., 2011. Urban Storm Water Managment
25. Ress, L. D., Hung, C.-L. J. & James, L. A., 2020. Impacts of urban drainage systems on stormwater hydrology: Rocky Branch Watershed, Columbia, South Carolina.
26. Sailor, D. J. & Bass, B., 2014. *Development and features of the Green Roof Energy Calculator (GREC),* s.l.: s.n.
27. Sandoval, V., Suárez, F., Vera, S. & Pinto, C., 2015. *Impact of the Properties of a Green Roof Substrate on its Hydraulic and Thermal Behavior.* s.l., s.n.
28. Seyedabadi. M. R., Eicker. U, Karimi. S., 2021. *Plant selection for green roofs and their impact on carbon sequestration and the building carbon footprint*
29. Sjödahl, E., 2018. *CHANGING PERSPECTIVES ON STORMWEATHER,* s.l.: s.n.
30. Søgnen, O.-G., n.d. *Norwegian building energy statistics; specific energy,* s.l.: s.n.
31. Soulis, K. X. et al., 2017. Simulation of green roof runoff under different substrate depths and.
32. Stovin, V., Vesuviano, G. & De-Ville, S., 2015. Defining green roof detention performance.
33. Stovin, V., Vesuviano, G. & Kasmin, H., 2012. The hydrologic performance of a green roof test bed under UK climatic conditions.
34. U.S. Environmental Protection Agency, 2018. *Estimating the environmental effects of green roofs: A.* s.l.:s.n.
35. United Nations, 2019. *World Urbanization Prospects,* s.l.: s.n.
36. VirginiaStovina, GianniVesuvianoa & HartiniKasmin, 2012. The hydrological performance of a green roof test bed under UK climatic conditions.
37. Zakrisson, A., 2020. *The Purple-Roof Concept.* [Online]
    Available at: https://www.purple-roof.com/post/what-is-the-difference-between-green-roof-retention-and-detention
    [Accessed 30 May 2022].

Appendix

Appendix A



Conceptual Analysis: Inclined Angle Vs Radiation increase – to conjecturing the Retention capacity and the speed of evapotranspiration

**To consider about reducing material embodied emissions, height is also taken as a parameter*

- 5 Degree & 15 Degree shows a higher functionality in retrofitting of buildings when the existing roof is a flat roof; the 15 Degree is appealing architecturally than 5 Degree

	Angle	Minimum Height	Maximum Height	Height Increase	Radition Increase	Total Radiation
	0	10	10	0.00%	0.00%	900
Increase of 0 Floors	5	10	11.75	17.50%	5.60%	950
Increase of 1 Floors	10	10	13.53	35.30%	7.77%	970
Increase of 1 Floors	15	10	15.36	53.60%	13.30%	1020
Increase of 2 Floors	20	10	17.28	72.80%	16.66%	1050
	30	10	21.55	115.50%	17.77%	1060