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URBAN AND REGIONAL PLANNING
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Multi-Duration Performance Assessment of LID Controls for Urban Hydraulic and Hydrological Invariance using SWMM

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Abstract

In the face of climate change in various parts of Italy, including Piedmont, the hydraulic and hydrological invariance (HHI) principle has been adopted as a measure to mitigate the adverse effects of new developments on hydraulic and hydrological-related risks caused by urban runoff. To satisfy the HHI principle, a new development should limit both peak discharge and total volume of runoff to under pre-development values. Low Impact Development (LID) controls, often categorized as green infrastructure, can be used to achieve HHI by mimicking natural processes of water, such as infiltration, evapotranspiration, and detention; however, their effectiveness to satisfy HHI just by themselves remains open to debate. Many factors can affect the performance and effectiveness of LID controls, including the type of LID control, its properties and the design storm duration and frequency. In Italy, design storm duration was traditionally chosen to be equal to the time of concentration T_c of the catchment; now it is preferred to be the result of a computational search of critical storm duration. In this thesis, by using EPA's SWMM software, multiple scenarios were simulated in a 1000sqm hypothetical urban plot in Turin with 600sqm of impermeable area, to analyze the feasibility of HHI using different LID controls and to understand the effect of design storm duration on LID control performance. At the start of the SWMM simulations, three different types of LID controls were used under different design storm durations ranging from 10 minutes to 24 hours for a return period of 50 years T_r=50 years, with a native soil of type C (curve number 70). The LID controls used were green roof, bioretention cell, and permeable pavement. The green roof was found to be the most suitable for our case study, as the bioretention cell required a large footprint, competing with that of the building, and the permeable pavement required more area than what was available to have a meaningful effect, making both of them spatially inefficient choices in the case study's dense, small urban catchment, where the roof is the primary source of runoff. Furthermore, the performance of two variants of extensive and intensive green roofs was analyzed in different design storm durations and different types of native soil. The results showed that, in general, both variants have more potential in controlling peak discharge while facing more difficulties in managing the total volume of runoff, with only complete coverage of impermeable areas by an intensive green roof being able to reach HHI in every simulated instance. Due to lower levels pre-development runoff in higher-infiltration soils the success of the LID controls in achieving HHI became less frequent moving from type D soil to type A soil, with HHI completely achievable with 70% of coverage by an intensive green roof in type D soil in all design storm durations, in comparison to achieve the same in type A soil, 100% coverage was needed. Furthermore, the analyses showed the inability of extensive green roofs to achieve HHI, with only 3 simulated instances of success by 100% of coverage in soil types D and C during short design storm durations, underlining the need for complementary storage volumes. Finally, the study concludes that in a dense urban plot, achieving HHI is more viable during longer design storm durations with lower intensities, especially while using lower coverages of intensive green roofs, with intensive green roofs being the most viable standalone option.

Keywords: Hydraulic and Hydrological Invariance, Low Impact Development, Green Roofs, Stormwater Management Model, Design Storm Duration, Urban Stormwater Management

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Glossary of Terms

Hydraulic and Hydrological Invariance	HHI
Storm Water Management Model	SWMM
Geographic Information System	GIS
Sustainable Development Goals	SDGs
Low Impact Development	LID
Curve Number	CN
Soil Conservation Service	SCS
Environmental Protection Agency	EPA
Sustainable Urban Drainage Systems	SUDS
Permeable Pavement	PP
Bioretention Cell	BR
Green Roof	GR
Extensive Green Roof	EGR
Intensive Green Roof	IGR
Peak Reduction	PR
Volume Reduction	VR
Effective Impervious Area	EIA
Hydrologic Soil Group	HSG
Nature-Based Solution	NBS
Impervious	Imp.
Pervious	Perv.

List of Units

Litre per second	lps
Square meter	sqm
Millimeters	mm
Hectares	ha
Minutes	min
Hours	hr
Millimeters per hour	mm/hr

Chapter 1. Introduction

1.1 Background and Context

Due to rapid urbanization and intense precipitation caused by climate change, managing the stormwater runoff is becoming a challenge in urban areas. The transformation of natural permeable surfaces into impermeable surfaces has resulted in increased stormwater runoff volumes and peak discharges, while also decreasing the times of concentration as water travels faster on artificial impermeable surfaces common in urban areas. This transformation has fundamentally altered urban hydrology, amplifying flood risk due to drainage infrastructure failure.

According to Westra et al. (2014), this challenge will intensify in the future as studies suggest an increase in both frequency and intensity of extreme precipitation events in many regions, and it is verified by CMCC (2020) that the same trend is true for Italy, as well as the high vulnerability of Italian cities to pluvial flood risk.

To mitigate urban runoff impacts, Low Impact Development (LID) controls, often categorized as Green Infrastructure or Sustainable Urban Drainage Systems (SUDS), can be used. LID controls such as green roofs, permeable pavement, and bioretention cells work by mimicking natural processes of water, such as infiltration, evapotranspiration, detention, and retention, all of which a traditional gray infrastructure lacks.

1.2 Regulatory Context: Hydraulic and Hydrological Invariance in Italy

One of the main governing frameworks for the design of stormwater management systems in Italy is the principle of *invarianza idraulica e idrologica* (Hydraulic and Hydrological Invariance, HHI). Under this regulatory framework, new urban developments are required to maintain both pre-development peak discharge rates (Hydraulic Invariance) and runoff volumes (Hydrological Invariance), thereby reducing the risk for downstream floods (Regione Lombardia, 2017). The Piedmont Region has established similar requirements to ensure that urbanization does not compromise the capacity of receiving water bodies or increase flood hazards.

The selection of design storm events is a core element of the application of HHI principles. As ARPA Piemonte (2014) suggests and as a common practice in Italy and many jurisdictions around the world, the design storm duration is considered equal to the time of concentration T_c of the catchment area. The time of concentration is the time it takes for water to travel from the hydraulically most distant point in the catchment to the outlet, and thus in theory corresponds to the storm duration that produces the maximum peak discharge. However, this approach presents a significant challenge for small catchments.

In a small urban catchment with extensive impervious surfaces, T_c values are often extremely short due to rapid runoff travel. The design storms that are selected based on these short T_c values have very high rainfall intensities, but may not present the total rainfall depths and volumes required to evaluate LID system performance under the most critical scenario possible. Shorter-duration storms may generate higher peak flows, but longer-duration events can produce greater runoff volumes that stress storage capacity and challenge the overall effectiveness of stormwater control measures, which highlights the need for examining different durations of rainfall.

1.3 The Design Storm Duration Problem

Logically, the "critical storm duration" (the duration that produces the maximum required storage or most adverse system performance) may differ from T_c, particularly for detention and retention systems, and this raises important questions about the reliance on T_c-based design storms for LID systems and their adequacy. Peak discharge and total runoff volume are different response variables in the critical storm duration concept, and the storm duration that produces the maximum peak may not be the same as that which generates the maximum volume.

Performance of LID controls due to their limited storage capacity is highly sensitive to both storm intensity and duration, and they rely on time-dependent processes such as infiltration and evapotranspiration in order to regain their storage capacity. Although some research, such as that of Orsi et al. (2025), has shown that LID performance varies substantially across different storm events, evaluation of how storm duration affects LID effectiveness in achieving Hydraulic and Hydrological Invariance in small urban plots remains limited.

1.4 Research Gap and Objectives

Regarding the regulatory frameworks requiring Hydraulic and Hydrological Invariance for the new development projects and the growing implementation of LID controls to achieve it, some critical knowledge gaps still exist about optimal design storm selection:

- Is a T_c-based design storm duration, which is usually very short in small urban plots, adequate for the design of LID controls to achieve HHI?
- How much do different storm durations affect LID performance in reducing peak flows and runoff volumes?
- Can LID controls be a standalone solution to achieve HHI?
- What is the most logical type of LID control to be used to achieve HHI?

This research addresses these gaps through a systematic evaluation of three common LID Control types under a range of design storm durations(ranging from 10 minutes to 24 hours for a 50-year return period) and further examines the performance of two Green Roof variants in different native soil types using the Storm Water Management Model (SWMM).

Chapter 2. Literature Review

2.1 Urbanization and the Hydrological Cycle

The rapid expansion of impervious surfaces, such as roofs, parking lots, and roads, has made fundamental changes to the natural cycle of water by eliminating infiltration. The transformation of natural surfaces effectively changes the urban landscape from a sponge to a conveyor belt for the runoff, as the rainfall turns into runoff immediately upon landing on impervious surfaces, which leads to heightened pluvial flood risk by stressing the traditional drainage infrastructures as well as hydrological costs caused by the imbalance of infiltration.

2.1.1 Climate Change and Extreme Precipitation in Italy

Climate change and the consequent shifting of climate regimes have made managing the urban runoff more challenging. As noted by Westra et al. (2014), global warming is causing a significant increase in both intensity and frequency of extreme rainfall events. Interestingly, according to Cramer et al. (2018), in warmer climates such as most parts of the Mediterranean, the frequency of extreme rainfall events can increase even when the mean precipitation is projected to decrease. Impervious surfaces and insufficient stormwater management systems add to the risk posed by these recurring flash floods in the Mediterranean countries.

The research done by the Euro-Mediterranean Center on Climate Change (CMCC, 2020) verifies the same patterns for Italy, while warning about the possibility of higher frequency and intensity of future rainfall events in Italy. The report warns about the exposure of Italian cities to the risk of flooding, which is worsened by specific reasons such as geographical and geo-hydrological characteristics of Italian territory, poor management of urbanization processes, and a rapid increase in land use dominated by impervious surfaces. In this context, compared to the present condition, the flood risk increases in all scenarios, and the most fragile parts of the population are the ones that are the most exposed to this increasing risk. Although People with low mobility, children, and the elderly are the most exposed, in a more general sense, the climatic risk related to floods affects the whole population’s safety, as well as infrastructure and services.

These risks make a transition from traditional stormwater management to Sustainable Urban Drainage Systems (SUDS) more attractive, if not necessary.

2.1.2 Sustainable Development Goals (SDGs)

From a wider planning view, urban runoff management is not just a technical problem; In fact, it is a core principle of a sustainable future, and this research addresses several Sustainable Development Goals (SDGs), specifically through some of their targets set forth by the United Nations (n.d.), which are presented below.

SDG11 (Sustainable Cities and Communities):

- **Target 11.5:** By 2030, significantly reduce the number of deaths and the number of people affected and substantially decrease the direct economic losses relative to global gross domestic product caused by disasters, including water-related disasters, with a focus on protecting the poor and people in vulnerable situations.
- **Target 11.B:** By 2020, substantially increase the number of cities and human settlements adopting and implementing integrated policies and plans towards inclusion, resource efficiency, mitigation and adaptation to climate change, resilience to disasters, and develop and implement, in line with the Sendai Framework for Disaster Risk Reduction 2015-2030, holistic disaster risk management at all levels.

SDG 13 (Climate Action):

- **Target 13.1:**Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries.
- **Target 13.2:**Integrate climate change measures into national policies, strategies and planning.

SDG 6 (Clean Water and Sanitation):

- **Target 6.5:** By 2030, implement integrated water resources management at all levels, including through transboundary cooperation as appropriate.
- **Target 6.6:** By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes.

It should be noted that although this research is done to evaluate the performance of LID Controls in the reduction of runoff, LID Controls and in general SUDS have many benefits that can help to achieve the SDGs mentioned above. Especially in the case of SDG 6

(Clean Water and Sanitation), these practices allow the achievement of the targets through the utilization of decentralized infrastructure to manage urban runoff, which can help in water resource management and restoring water-related ecosystems by elevating natural behaviors such as infiltration.

2.1.3 The Role of Urban Planning in Modern Flood Mitigation Methods

In modern planning, there is a significant transition from grey to green, and the move towards SUDS through using LID Controls on site scales is a part of this transition. Rather than seeing the rainwater as a product that needs to be treated and removed, planning frameworks such as Piano Di Resilienza Climatica (Città di Torino, 2020) now view it as a resource that should be retained and reused if possible. This is where the concept of Hydraulic and Hydrological Invariance comes into view as a regulatory requirement, to make the transition from Grey Infrastructure to Green Infrastructure happen, and change the theoretical sustainability into development standards.

2.2 Low Impact Development (LID) Controls

2.2.1 LID Performance and HHI

As mentioned before, Low Impact Development (LID) Controls, also known as part of broader Sustainable Urban Drainage Systems (SUDS), allow for decentralized stormwater management at the site scale by effectively capturing the whole or a part of the rainfall. Although multiple types of LID Controls can be used to achieve the goal of capturing the runoff, in a small urban plot striving to achieve the HHI, the choices remain more limited, as the land value is at a premium, and the land use subsequently is dominated by this fact. Nevertheless, a literature review was conducted on studies examining the effectiveness of LID Controls in reducing Peak Discharge and Total Volume of runoff, and for this the most spatially effective ones were considered due to a small urban plot’s limitations. These were Green Roof, Permeable Pavement, and Bioretention Cell, all of which offer delayed runoff by detention as well as natural hydrological processes such as infiltration and evapotranspiration.

As a main driver of this study, Orsi et al. (2025) found out the general positive effects of LID Controls on mitigating the effects of urbanization on runoff production, while mentioning the effect of rainfall characteristics and land use conversion on the effectiveness of LID Controls. They introduce the EIA (Effective Impervious Area) as a measure of the Impervious Area in their case study area, and the EIA_{red}(Effective Impervious Area Reduction) as an index to the replacement of impervious area by LID Controls. The LID Control types used in their study were Permeable Pavement and an Extensive Green Roof variant, which in separate scenarios, covered and replaced different percentages of the case study catchment's impervious area. Their research showed that the HHI principle is barely achievable by the standard implementation of LID Controls.

Orsi et al. (2025) conclude that despite their positive results in reducing runoff, using LID Controls for achieving the HHI was not possible because the natural (pre-development) state's peak discharge and total volume runoff, which is established by Italian regulations and guidelines, in their words, were too demanding. This is true as reestablishing natural runoff conditions can be very challenging; however, in their case there are two points that worsen this challenge. First, the high imperviousness percentage of their case study (72.5%) and second is the low usage of this impervious area to implement the LID Controls (EIA_{red} is limited to a maximum of 50%), of course the reason for the second one is the presence of roads in their wider case study area which cannot be used for LID Control implementation. In a smaller case study plot that lacks incompatible surfaces (surfaces that cannot be used for LID Control implementation, such as roads), theoretically, the EIA_{red} values can be significantly higher, which in turn can yield different results. Their results show that the Green Roof has a superior performance compared to the Permeable Pavement, which is interesting since the Green Roof configuration used is a light extensive variant with a shallow depth of soil, the reason for this can be the configuration used for the Permeable Pavement which has a drain with a high flow coefficient, which, when combined with other settings presented in the study can lead to poor performance of Permeable Pavement.

Figure 2.1: An Extensive Green Roof

Figure 2.2: Permeable Pavement

Other literature also examined the performance of LID Controls in terms of Peak Reduction and Volume Reduction. Palla and Gnecco (2020) note that their research shows, under every scenario simulated with input data obtained from three Italian sites, Green Roof proved to have a positive impact on Peak Discharge and Total Volume; however, its retention and detention performance were negatively affected by the higher depth and intensity of the rainfall.

Studies suggest a higher potential of the Bioretention Cell in reducing runoff, with Wicaksono et al. (2025) mentioning high values of Peak Reduction (80-92%) for the scenarios simulated in the study. In their research, they used coverages of 5%,10%, and 20% of the total case study area for the Bioretention surface, which can be fairly manageable even in small urban plots; however, the design rainfall used in the research has a return period of just two years T_r=2 years, with a total rainfall depth of 82.9 mm for a 24-hour duration which is significantly lower than the total rainfall depth of T_r=50 years typically asked in HHI requirements for new developments, and as mentioned before Palla and Gnecco (2020) argue that the performance of the Green Roof was negatively affected by a higher depth of rainfall; this can also be true in the case of the Bioretention Cell as the higher depth of rainfall can saturate and eventually overwhelm the Bioretention Cell, especially since, unlike the other two types of LID Controls discussed in this study it usually covers areas other than its surface through connections to roofs or its surrounding area. In terms of the Volume Reduction potential of the Bioretention Cell, a study by Winston et al. (2016) showed that, over a period of time, Bioretention Cells were successful in reducing the runoff volumes by 36% to 59% despite the low permeability of the native clay soil in which they were constructed. Although their study was conducted in real-world conditions, which did not involve the heavier rainfall such as T_r = 50, they mention that during the few short rainfalls with heavier intensities(over 99 mm/hr) the Bioretention Cells were successful in reducing the Peak Runoff by 53-88%.

Figure 2.3: A Bioretention Cell

2.2.2 The Spatial Placement of LID Controls

According to the US Environmental Protection Agency (2000), the original intent of LID Controls was to achieve a natural hydrology by the use of integrated measures and the site layout, and the natural hydrology mentioned is basically the same as HHI, which, according to EPA, is achieved by using a landscape that is functionally equivalent to the pre-development state in terms of natural hydrologic processes such as infiltration and evapotranspiration. This implies the original intent of LID Controls was also to achieve HHI in a small-scale plot as a part of a wider catchment, in other words, as noted by Fletcher et al. (2015), the term LID was used to introduce a practice that involved the use of small-scale water treatment systems such as Bioretention Cells and Green Roof and to distinguish it from the common stormwater management at the time which involved delivering the rainwater to big end of the pipe detentions.

Based on these statements, it is easy to understand the importance of the spatial placement of LID Controls, or in other words, the feasibility of their implementation. In this case, the Green Roof has a clear advantage over the other two types of LID Controls, as it uses the building’s footprint (the roof). The roof's impervious surface, which is the installation ground for the Green Roof, is also a major contributor to the urban runoff by conveying the rainwater, usually directly to the stormwater system. Covering this impervious area not only reduces the impervious surface of the site but also does not incur any spatial costs. In the case of other LID Control types, Wicaksono et al. (2025) mention that before implementing Bioretention Cells, careful attention should be paid to several aspects, including the placement and the size, as these LID Controls usually occupy a significant area in order to have a meaningful effect, and as observed in the study carried out by Orsi et al. (2025), even in the presence of significant surface area in need of paving (which is a rarity in small plots), Permeable Pavements cannot be used in all of them.

2.3 The Regulatory Framework for Hydraulic and Hydrological Invariance (HHI)

In Italian legislation, the concept of Hydraulic and Hydrological Invariance sets the most restrictive limits regarding urban runoff; this concept requires that the developments which cover parts of the soil with impervious surfaces compensate for the added runoff with measures that ensure the runoff matches the natural pre-development state.

2.3.1 National and Regional Legislative Context

At the national level, DECRETO LEGISLATIVO 3 aprile 2006, n. 152. (Legislative Decree 152/2006) sets the general framework for managing hydrological risks and protecting water resources through articles 113 and 101; however, as a general guideline, there is no direct mention of HHI, and the implementation of it is delegated to regional authorities.

While there is no single unified law for the implementation of HHI in the Piedmont region, the principle is enforced by means of a series of technical regulations and territorial planning instruments. Regolamento Regionale n. 1/R of 20 February 2006 and its subsequent updates govern the stormwater runoff generally, while Deliberazione della Giunta Regionale (D.G.R.) 24 Marzo 2025, n. 8-905. Which updated the previous D.G.R. 12 Dicembre 2017, n. 53-5814 provides details on HHI in annex IV. In local building codes, the shift towards the HHI is also observed, as by incorporating regional guidelines, municipal regulations direct a push towards Nature-Based Solutions (NBS) such as LID Controls.

2.3.2 Principles of Invariance

As noted by Orsi et al. (2025), HHI compliance requires the satisfaction of two criteria.

- **Hydraulic Invariance**: This principle ensures that the peak discharge of runoff(Q_{Peak})does not exceed the values of the pre-development state.
- **Hydrological Invariance**: This is a more rigorous principle requiring that the total volume of runoff(V_{Total}) should not exceed the values of the pre-development state.

2.4 Technical Challenges and Knowledge Gaps on HHI Compliance

The physical configuration of LID Controls is the primary factor deciding their performance. This is highlighted by Nazarpour, Gnecco, and Palla (2024) in their systematic review on the efficiency of Bioretention Cells, as they note that there is a clear consensus by other researchers that the soil media depth of Bioretention Cells has a fundamental effect on their performance, as Bioretention Cells with higher soil media depth also have a higher Volume Reduction, the other key note in their review is the importance of the size of the Bioretention Cell as a variable. These findings can be directly connected to other types of LID Controls, especially Green Roofs. In Green Roofs, while the vegetative layer contributes to evapotranspiration, it is the substrate layer's porous space that provides the storage volume necessary for intercepting the rainwater.

2.4.1 Substrate Depth

While shallow substrate depths in LID Controls, such as Extensive Green Roofs, may be very effective for short-duration rains with low intensity, they can reach a saturation point during heavier rain events that can potentially reduce their effectiveness, as noted by Stovin et al. (2012) in their long-term monitoring of a Green Roof with shallow media depth the Green Roof's maximum retention percentage decreased with higher rainfall depths; however, contrary to this there are other studies on the effect of the media depth on the performance of LID Controls with different conclusions, Razzaghmanesh and Beecham (2014) and Dietz (2007) both concluded that the media depth did not have a significant effect on the performance of the Green Roof with Razzaghmanesh and Beecham (2014) mentioning that the only difference was higher Peak Reduction of Intensive Green Roof variant, and in his review, Dietz (2007) discusses that studies have shown the increase of substrate depth in Extensive Green Roofs does not necessarily improve performance, however the rainfall events used during both of these studies have a much lower depths and intensities compared to the extreme standards asked for HHI (T_r=50 years).

2.4.2 Native Soil Sensitivity

A significant gap remains in the relation between LID Controls implementation to achieve Hydraulic and Hydrological Invariance and the effect of the native geological context on this. Most of the existing studies evaluate the effectiveness of LID Controls against a fixed baseline, either as a pure performance study of the LID Control itself or considering just one type of native soil for the site, thus neglecting how the Hydrologic Soil Group (HSG) of the site affects the baseline to achieve HHI. This study tries to address these gaps by simulating different LID Control configurations in different soil types and examining their success in reaching the natural runoff state required by HHI.

Chapter 3. Materials and Methods

3.1 Study Area

The study is based on a hypothetical urban plot in the city of Turin in the Piedmont region and was specifically arranged to represent the typical density of a new small development. The total area of the plot is 1000 sqm, with a slope of 5% in the pre-development natural state. In the post-development state, the surface of the plot is divided into two main components: an impermeable section with 600 sqm area representing a building roof (or a paved parking area in case of scenarios related to Permeable Pavement simulation), and a permeable section with 400 sqm area representing the peripheral pervious area maintained as natural ground. As it is clear, this configuration yields an imperviousness ratio of 60% for the plot. Two spatial configurations are represented in Figures 3.1 and 3.2.

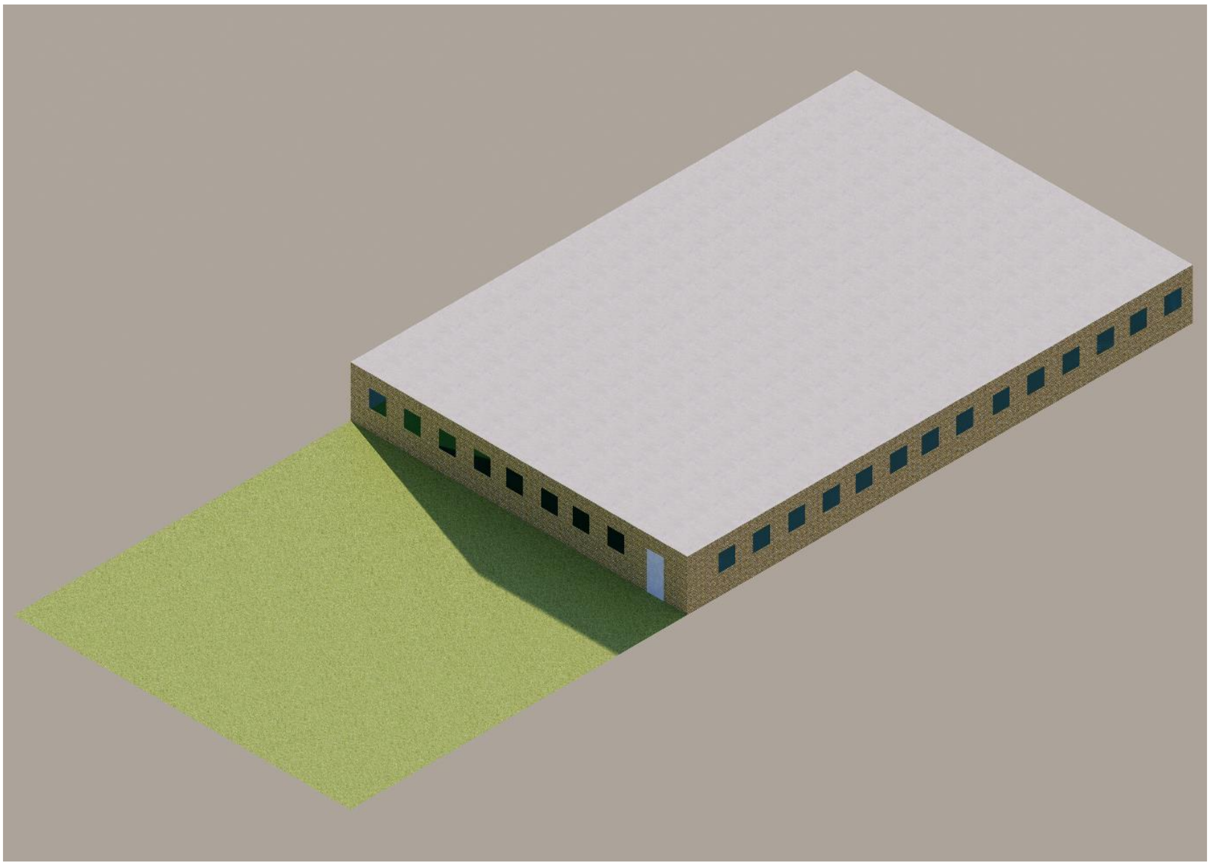

Figure 3.1: 3D model of the case study with a building roof as the impervious area

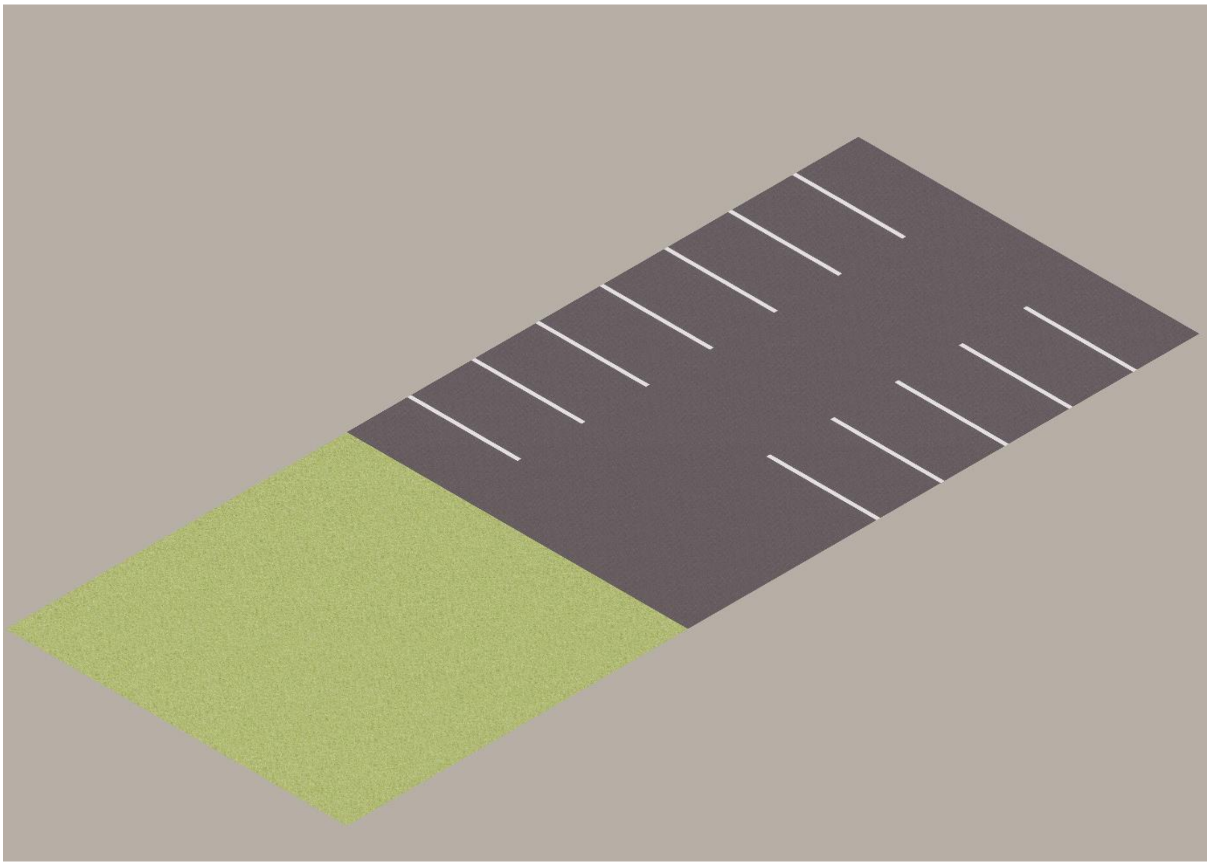

Figure 3.2: 3D model of the case study with a paved parking area as the impervious area

3.2 Rainfall Modelling

3.2.1 Rainfall Data Acquisition

The rainfall input for the simulations was derived from the geoportal of ARPA Piemonte. To satisfy the requirements of the HHI principle, for the location of the case study near Parco della Pellerina in Turin, the rainfall amount for a return period of 50 years (T_r = 50 years) Based on the Generalized Extreme Value (GEV) distribution, was acquired.

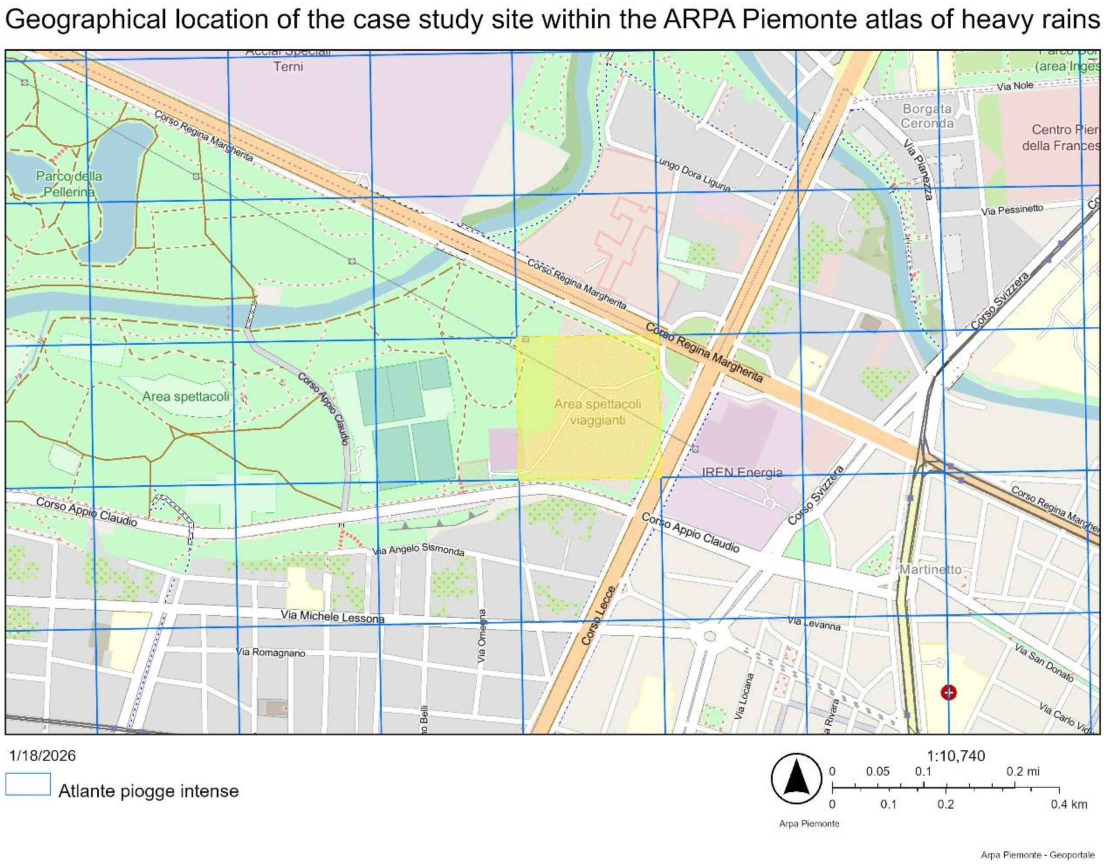

Figure 3.3 The geographical position of the case study within the atlas of heavy rains (Source: ARPA Piemonte)

Table 3.1. rainfall depths for different return periods at the case study location (Source: ARPA Piemonte)

Rainfall amount for different return periods in Piedmont (mm) - GEV distribution							
	2	**5**	**10**	**20**	**50**	**100**	**200**
10 minutes	18	24.4	28.9	33.3	**39.2**	43.9	48.7
20 minutes	21.8	29.6	34.9	40.3	**47.5**	53.1	58.9
30 minutes	24.3	32.9	38.9	44.8	**52.9**	59.1	65.6
1 hour	29.1	39.4	46.5	53.7	**63.3**	70.8	78.6
3 hours	38.6	52.2	61.7	71.2	**83.9**	93.9	104.2
6 hours	46.1	62.4	73.8	85	**100.3**	112.2	124.5
12 hours	55.1	74.6	88.1	101.6	**119.8**	134.1	148.8
24 hours	65.9	89.1	105.3	121.4	**143.2**	160.2	177.8

3.2.2 Time Series Generation

In order to have a sufficient resolution for short-duration rainfall while maintaining consistency in long-duration rainfalls, a time step equal to 10 minutes was chosen, and then the total rainfall depth of each duration was distributed evenly using the time steps of 10 minutes across the event.

3.2.3 The Simulation Input Table

Table 3.2. Division of design storms into 10-minute intervals for SWMM Time Series (T_r = 50)

Storm Duration	Total Depth (mm)	No. of 10-minute Steps	Rainfall Depth per Step (mm)	Intensity (mm/hr)
10 minutes	39.2	1	39.2	235.2
20 minutes	47.5	2	23.75	142.5
30 minutes	52.9	3	17.633	105.7
1 hour	63.3	6	10.55	63.3
3 hours	83.9	18	4.6611	27.96
6 hours	100.3	36	2.7861	16.68
12 hours	119.8	72	1.6638	9.96
24 hours	143.2	144	0.99444	5.94

3.3 Simulation Tool: EPA SWMM 5.2

The simulations were conducted using SWMM software version 5.2. SWMM stands for Storm Water Management Model, it was developed by The US Environmental Protection Agency (EPA) in 1971 and has undergone several major upgrades since then. It is one of the tools widely used as a dynamic runoff simulation model for single-event or long-term simulations of both runoff quantity and quality in urban and non-urban areas.

3.3.1 Infiltration Model

For infiltration losses, the Soil Conservation Service Curve Number (SCS-CN) method was used within the SWMM environment. Using this method, which accounts for the combined effect of soil group and cover conditions, first CN70 was used as the primary baseline, and later CN35, CN56, and CN77 were used to represent soil types A, B, and D, respectively, for sensitivity analysis.

Table 3.3: Curve Numbers used for simulations

Hydrologic Soil Group (HSG)	Soil Characteristics	CN Value	Runoff Potential
A	Deep sand, thin silt, aggregated silts	35	Low (high infiltration)
B	Sandy loam	56	Moderately low
C	Clay loam	70	Moderately high
D	Heavy plastic clay	77	High (low infiltration)

3.3.2 Subcatchment Parameters

The area of the subcatchment was considered to be 1000 sqm (0.1ha), with 60% imperviousness in post-development scenarios. As mentioned above, the slope in the pre-development scenarios was set to 5%; this was reduced to 0.5% in post-development scenarios to represent the urbanization. The width of the The subcatchment was set to 50 m to represent a short flow path of water. Other parameter values were unchanged from SWMM defaults.

3.3.3 Subarea Routing

The case study was modeled as a single subcatchment in which runoff for both pervious and impervious areas is directed to the outlet by setting the subarea routing option on 'OUTLET' in subcatchment properties in SWMM. However, in scenarios involving LID Controls, the option 'Return all Outflow to Pervious Area' was enabled in LID Usage Editor in SWMM, which means the outflow from LID Controls is first routed to the pervious area, mimicking a natural drainage scenario.

3.4 LID Control Implementation

For modelling the LID Controls, the values used for their parameters were chosen to be close to standard practices in the industry.

3.4.1 Green Roofs

In SWMM, Green Roofs are modeled as a three-layer system formed by surface, storage, and drainage mat layers. Two different kinds of extensive and intensive green roof variants were used in simulations with varying layer thicknesses to examine the impact of media depth on HHI compliance.

Table 3.4: Technical parameters for Green Roof variants in EPA SWMM

Layer	Parameter	Unit	Extensive	Intensive
Surface	Berm Height	mm	0	50
	Vegetation Volume	%	0	0
	Surface Roughness	(Manning's n)	0.1	0.1
	Surface Slope	%	1	1
Soil	Thickness	mm	150	500
	Porosity	-	0.5	0.5
	Field Capacity	-	0.2	0.2
	Wilting Point	-	0.1	0.1
	Conductivity	mm/hr	12.5	12.5
	Conductivity Slope	-	50	50
	Suction Head	mm	70	70
Drainage	Thickness	mm	20	100
	Void Fraction	-	0.5	0.5
	Roughness	(Manning's n)	0.1	0.1

3.4.2 Bioretention Cell and Permeable Pavement

Unlike the green roof systems, Permeable Pavement consists of a porous surface layer and a storage layer of coarse-graded stone. The Permeable Pavement used in simulations lacks an underdrain, meaning for recovery, it relies completely on infiltration into the native soil through seepage. The Bioretention Cell (BR) variant used represents the most complex LID implemented in this study. The BR acts as an infiltration basin for runoff generated by 600 sqm of roof or parking area. With an overall depth of 1000 mm and 150 mm of ponding depth, the Bioretention Cell is able to store the runoff, which is followed by slower infiltration into the soil media and eventual infiltration into the native soil. Like Permeable Pavement, the BR system implemented is infiltration-only and relies on infiltration into the native soil for recovery.

Table 3.5: Technical parameters for Permeable Pavement in EPA SWMM

Layer	Parameter	Unit	Value
Surface	Surface Roughness	(Manning's n)	0.1
	Surface Slope	%	1
Pavement	Thickness	mm	100
	Void Ratio	-	0.2
	Permeability	mm/hr	360
	Clogging Factor	-	0
Storage	Thickness	mm	150
	Void Ratio	-	0.5
	Seepage Rate	mm/hr	1.2
	Clogging Factor	-	0
Drain	Control Type	-	None (No Drain)

Table 3.6: Technical parameters for the Bioretention Cell in EPA SWMM

Layer	Parameter	Unit	Value
Surface	Berm Height	mm	150
	Vegetation Volume	%	0
	Surface Roughness	(Manning's n)	0.1
	Surface Slope	%	1
Soil	Thickness	mm	500
	Porosity	-	0.5
	Field Capacity	-	0.2
	Wilting Point	-	0.1
	Conductivity	mm/hr	12.5
	Conductivity Slope	-	10
	Suction Head	mm	70
Storage	Thickness	mm	500
	Void Ratio	-	0.75
	Seepage Rate	mm/hr	0.5
Drain	Control Type	-	None (No Drain)

3.5 The HHI Framework

3.5.1 The Evaluation Criteria

To satisfy the HHI principle, a new development should limit both peak discharge and total volume of runoff to under pre-development values. The LID Controls performance was evaluated on these two primary indicators.

3.5.2 Hydraulic Invariance (Peak Discharge)

The goal is to ensure that the maximum peak discharge in post-development conditions does not exceed that of the pre-development (natural) conditions.

$$Q_{Peak,Post} \leq Q_{Peak,Pre}$$

3.5.3 Hydrological Invariance (Total Volume)

The goal is to maintain the total volume of runoff to values equal to or lower than the pre-development (natural) value.

$$V_{Total,Post} \leq V_{Total,Pre}$$

3.6 Analysis Framework

This section defines the logic behind the performance comparison of the LID controls and indicators used.

3.6.1 Surface Occupation

An important aspect of this study is the manner in which each LID control interacts with the site's surface. To allow for a direct comparison between Green Roof and Permeable Pavement, the total potential area for both of them was set as 600sqm. As the coverage percentage of these two types of LID control increases, they cover or replace more of the surfaces that are impervious by nature (the roof or the parking area), resulting in a reduction of the Effective Impervious Area (EIA) of the site.

In contrast, the Bioretention Cell is implemented in the pervious section of the case study plot, and as the coverage percentage of the Bioretention Cell increases, the EIA of the site stays constantly at 60%. This logic is based on the realities of urban design, as in the design process, Green Roof and Permeable Pavement usually cover or replace surfaces that are potentially impervious due to their function, while the Bioretention Cell is usually implemented on a pervious surface to allow for more retention capacity.

Table 3.7 Subcatchment and LID Area

Scenario	Perv. (sqm)	Perv. (%)	LID (sqm)	LID (%)	Imp. (sqm)	Imp. (%)
Pre-Development (natural)	1000	100	0	0	0	0
Post-Development (urbanized)	400	40	0	0	600	60
GR30%	400	40	180	18	420	42
GR50%	400	40	300	30	300	30
GR70%	400	40	420	42	180	18
GR100%	400	40	600	60	0	0
PR30%	400	40	180	18	420	42
PR50%	400	40	300	30	300	30
PR70%	400	40	420	42	180	18
PR100%	400	40	600	60	0	0
BR30%	310	31	90	9	600	60
BR50%	250	25	150	15	600	60
BR70%	190	19	210	21	600	60
BR100%	100	10	300	30	600	60

3.6.2 Performance Indicators

In order to better understand and compare performance across different design storm durations, the reductions in peak discharge (Peak Reduction, PR) and total volume (Volume Reduction, VR) are calculated as percentages relative to the post-development (urbanized) scenario.

$$\boldsymbol{PR}\ (\%) = \frac{\mathbf{Q_{Peak,Post}} - \mathbf{Q_{Peak,LID}}}{\mathbf{Q_{Peak,Post}}} \cdot \mathbf{100}$$

$$\boldsymbol{VR}\ (\%) = \frac{\mathbf{V_{Total,Post}} - \mathbf{V_{Total,LID}}}{\mathbf{V_{Total,Post}}} \cdot \mathbf{100}$$

Where $\mathbf{Q_{Peak,Post}}$ and $\mathbf{V_{Total,Post}}$ respectively represent peak discharge and total volume runoff of the post-development (urbanized scenario), and where $\mathbf{Q_{Peak,LID}}$ and $\mathbf{V_{Total,LID}}$ respectively, are the peak discharge and the total volume runoff of the LID scenario.

3.6.3 HHI Compliance Targets

As mentioned before, HHI is achieved when the implemented LID Control successfully reduces the runoff to levels equal to or lower than the levels of pre-development (natural) conditions. For each simulation, an HHI target was calculated as a percentage.

Peak Reduction Needed: the minimum $\boldsymbol{PR}$ needed to reach the pre-development peak discharge ($\mathbf{Q_{Peak,Pre}}$).

Volume Reduction Needed: the minimum $\boldsymbol{VR}$ needed to reach the pre-development total volume runoff ($\mathbf{V_{Total,Pre}}$).

Chapter 4. Results and Discussion

4.1 Preliminary Considerations

The objective of this chapter is to evaluate and compare the performance of different types of Low Impact Development (LID) Controls and their ability to achieve the HHI principle as standalone options for a small urban site with 1000 sqm area. The analysis is focused on the comparison of the performance of the LID Controls at first, before moving on to further analyze the most spatially viable options, which are Green Roofs.

To establish a 100% (maximum) coverage scenario for each LID, the following areas were defined based on the constraints of the case study plot:

- Green Roof and Permeable Pavement (600 sqm): this represents the full usage of the building roof area for Green Roof or the alternative parking area for Permeable Pavement, and is equal to the total area of impervious area.
- Bioretention Cell (300 sqm): this represents 75% of the total pervious area of the case study plot, and is basically the maximum hypothetical area for implementation of the Bioretention Cell without compromising the utilization of impervious area.

For each type of LID Control, multiple scenarios with different coverages of LID under all eight design storm durations were carried out.

It should be noted that the goal of defining such high maximum coverages was to determine the real potential of each LID type in reducing runoff and reaching HHI, and this idealized potential of the LID Controls does not necessarily translate into practice due to spatial inconvenience. For example, in the case of Permeable Pavement, it was decided to define a maximum coverage equal to that of Green Roof's by replacing the building roof area with an impervious parking area, so the Permeable Pavement can replace this impervious area in the case study plot. This was done in part because the implementation of the Permeable Pavement in pervious areas of the case study plot seemed illogical when compared to the Green Roof, which was implemented on the impervious surface of the building roof. The other reason was that it was observed that the Permeable Pavement yielded poor results when its coverage area was low.

4.2 Comprehensive Performance Analysis

This section presents the simulation of the three types of LID Controls, including Bioretention Cell, Permeable Pavement, and Green Roof. These LID controls were implemented in different coverage scenarios across eight design storm durations to evaluate their ability to reduce peak discharge (Q_{Peak})and total volume (V_{Total}). The simulations were carried out with a native soil of hydrologic soil group C (CN70).

4.2.1 Bioretention Cell Performance

This section analyzes the performance of the Bioretention Cell across eight rainfall durations. The unit was designed to receive and treat the runoff generated by the site's 600 sqm of impervious area.

Table 4.1: Peak Discharge (LPS) for Bioretention Cell (CN70), Shaded cells indicate compliance with HHI requirements ($Q_{Peak,LID} \leq Q_{Peak,Pre}$)

scenario	10min	20min	30min	1hr	3hr	6hr	12hr	24hr
natural	20.15	17.64	14.77	10.15	5.23	3.36	2.14	1.35
urbanized	46.65	30.6	23.45	14.59	6.75	4.13	2.52	1.53
BR30%	16.95	27.86	22.74	14.01	6.25	3.69	2.12	1.23
BR50%	6.7	9.7	12.48	13.49	5.89	3.37	1.85	1.03
BR70%	6.37	5.58	4.67	4.79	5.51	3.06	1.55	0.43
BR100%	5.84	5	4.16	2.85	1.46	0.94	0.6	0.38

Table 4.2: Total Volume (Liters) for Bioretention Cell (CN70), Shaded cells indicate compliance with HHI requirements ($V_{Total,LID} \leq V_{Total,Pre}$)

scenario	10min	20min	30min	1hr	3hr	6hr	12hr	24hr
natural	7044	11470	14480	21330	35790	47700	62540	81310
urbanized	26740	33250	37660	46790	64520	79350	96940	118420
BR30%	7650	15870	20810	28730	43240	52960	61950	71140
BR50%	2460	6740	11100	18260	30100	36800	40640	42400
BR70%	2350	3620	4580	8340	17550	21570	21270	25690
BR100%	2170	3300	4140	5980	10020	13360	17510	22770

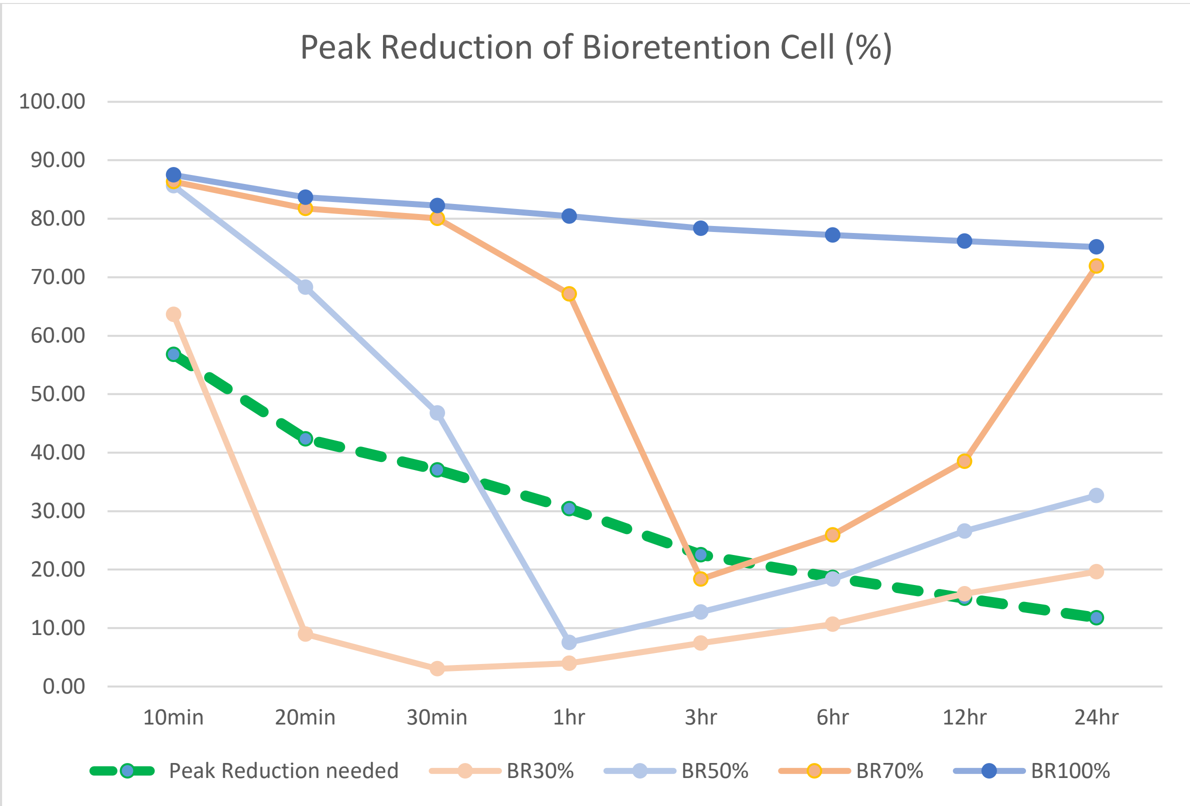

Figure 4.1: Peak Reduction graph for Bioretention Cell scenarios across different design storm durations (CN70)

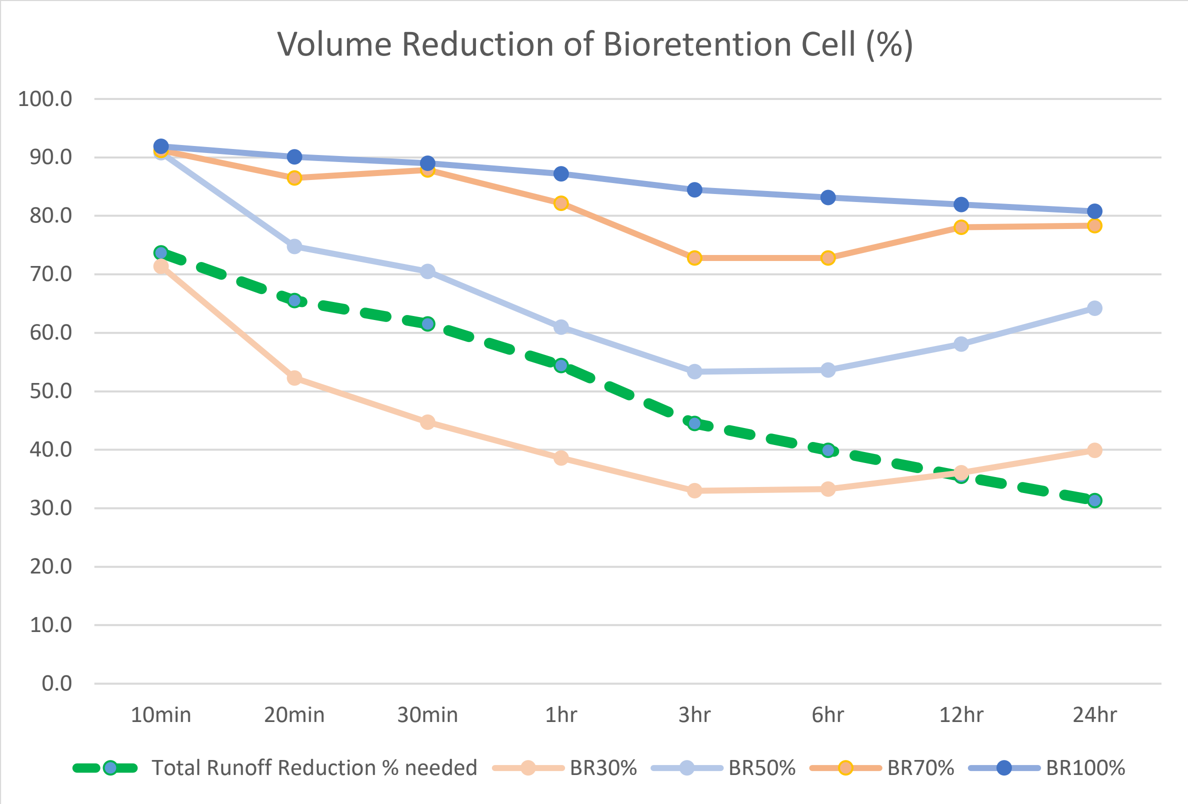

Figure 4.2: Total Volume Reduction graph for Bioretention Cell scenarios across different design storm durations (CN70)

As illustrated in comparative analyses of Peak Reduction (Figure 4.1) and Volume Reduction (Figure 4.2), the Bioretention Cell shows a non-linear performance trend across different design storm durations. With 30% coverage (90 sqm), it fails to achieve the HHI in almost every duration, which is more pronounced in Volume Reduction.

There is a significant improvement in the performance with 70% coverage (210 sqm), the bigger surface area and ponding volume allow the bioretention to successfully reduce the peak discharge to levels below the pre-development conditions in almost all scenarios, while the volume reduction remains constantly at much higher levels needed. The trend of improvement in peak reduction observed after 3hr rainfall duration shows that the Bioretention Cell system can utilize its storage volume more efficiently with the reduction of rainfall intensity, leading to more infiltration into the native soil.

4.2.2 Permeable Pavement Performance

Unlike the Bioretention Cell, the Permeable Pavement was not designed to receive any runoff generated by the impervious area, and only received the rainfall that fell directly on its surface area.

Table 4.3: Peak Discharge (LPS) for Permeable Pavement (CN70), Shaded cells indicate compliance with HHI requirements ($Q_{Peak,LID} \leq Q_{Peak,Pre}$)

scenario	10min	20min	30min	1hr	3hr	6hr	12hr	24hr
natural	20.15	17.64	14.77	10.15	5.23	3.36	2.14	1.35
urbanized	46.65	30.6	23.45	14.59	6.75	4.13	2.52	1.53
PP30%	30.77	21.55	16.94	10.84	6.45	3.97	2.41	1.45
PP50%	22.13	16.42	13.18	8.61	6.27	3.92	2.36	1.4
PP70%	15.09	12.05	9.89	6.62	6.05	3.9	2.33	1.37
PP100%	7.45	6.85	5.82	4.04	5.71	3.93	2.32	1.33

Table 4.4: Total Volume (Liters) for Permeable Pavement (CN70), Shaded cells indicate compliance with HHI requirements ($V_{Total,LID} \leq V_{Total,Pre}$)

scenario	10min	20min	30min	1hr	3hr	6hr	12hr	24hr
natural	7044	11470	14480	21330	35790	47700	62540	81310
urbanized	26740	33250	37660	46790	64520	79350	96940	118420
PP30%	16630	21360	24800	31500	47630	61580	77730	96420
PP50%	11300	14980	17790	23180	37920	51590	66930	83900
PP70%	7080	9830	11980	16200	29640	43120	57760	73130
PP100%	2710	4310	5530	8520	20180	33400	47150	60330

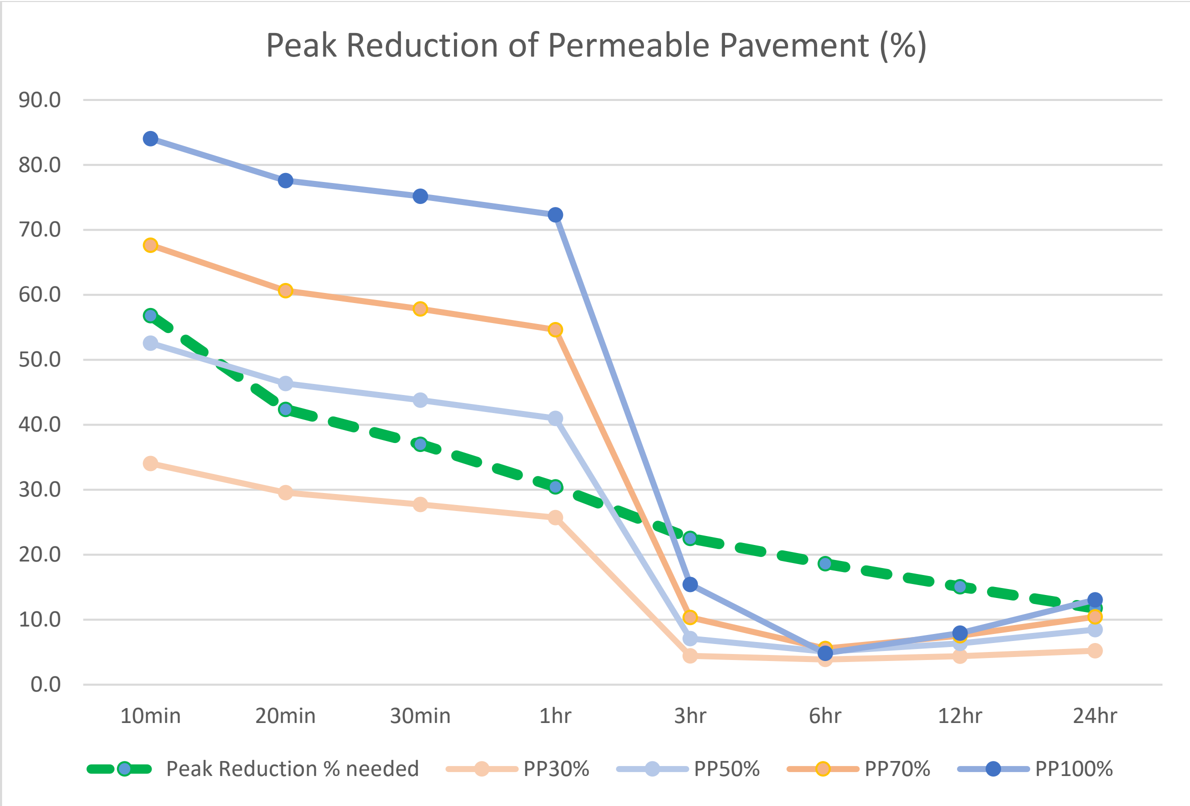

Figure 4.3: Peak Reduction graph for Permeable Pavement scenarios across different design storm durations (CN70)

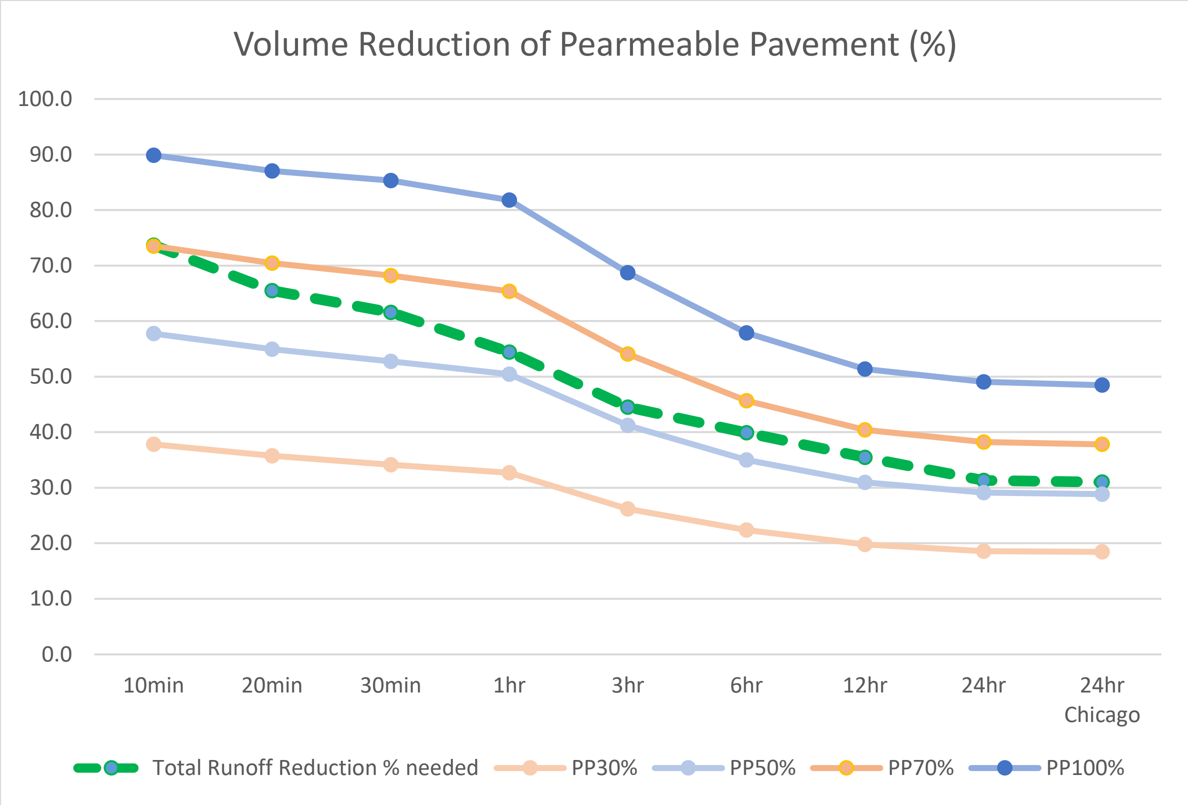

Figure 4.4: Total Volume Reduction graph for Permeable Pavement scenarios across different design storm durations (CN70)

Unlike the Bioretention Cell, the Permeable Pavement shows a significant fall in efficiency after 1 hour mark. As shown in the comparative analyses of Peak reduction (Figure 4.3), there is a dramatic decrease in Peak Reduction between the 1hour and 3hour durations. Even at 100% coverage, there is a steep drop in performance, whereas the Peak Reduction falls from 72.3 % in 1-hour design storm duration to 15.4% in 3-hour design storm duration. In simulations using longer than 3-hour rainfall durations, in all but one of the scenarios, Permeable Pavement fails to achieve hydraulic invariance. The reason for this decline in PR performance is the shallow storage layer of permeable pavement, which once saturated by higher depths of rainfall, causes the LID performance to collapse.

In comparison, the Volume Reduction of Permeable Pavement (Figure 4.4) is more stable than its Peak Reduction, but it still shows a steady decline as duration increases. With 30% and 50% coverages completely failing to achieve hydrological invariance, higher coverages are needed to reach the VR targets needed for hydrological invariance.

4.2.3 Extensive Green Roof Performance

The Extensive Green Roof was simulated with a 150 mm soil layer to represent the most common lightweight Green Roof configuration; the performance analysis of this variant of Green Roof is presented in this section.

Table 4.5: Peak Discharge (LPS) for Extensive Green Roof (CN70), Shaded cells indicate compliance with HHI requirements ($Q_{Peak,LID} \leq Q_{Peak,Pre}$)

scenario	10min	20min	30min	1hr	3hr	6hr	12hr	24hr
natural	20.15	17.64	14.77	10.15	5.23	3.36	2.14	1.35
urbanized	46.65	30.6	23.45	14.59	6.75	4.13	2.52	1.53
EGR30%	30.77	25.87	20.46	12.77	6.44	4.03	2.47	1.51
EGR50%	22.13	23.84	18.99	11.8	6.22	4.02	2.46	1.5
EGR70%	15.09	20.3	17.8	11.03	6.01	4.04	2.47	1.51
EGR100%	11.24	16.12	16.35	10.4	5.79	4.13	2.52	1.53

Table 4.6: Total Volume (Liters) for Extensive Green Roof (CN70), Shaded cells indicate compliance with HHI requirements ($V_{Total,LID} \leq V_{Total,Pre}$)

scenario	10min	20min	30min	1hr	3hr	6hr	12hr	24hr
natural	7044	11470	14480	21330	35790	47700	62540	81310
urbanized	26740	33250	37660	46790	64520	79350	96940	118420
EGR30%	16630	23470	28140	36060	52090	66700	84270	105410
EGR50%	11300	18960	23180	29780	45310	60140	77780	98880
EGR70%	7880	15580	19540	25500	39900	55240	72980	94150
EGR100%	6150	13080	16870	23290	34920	50740	69010	91020

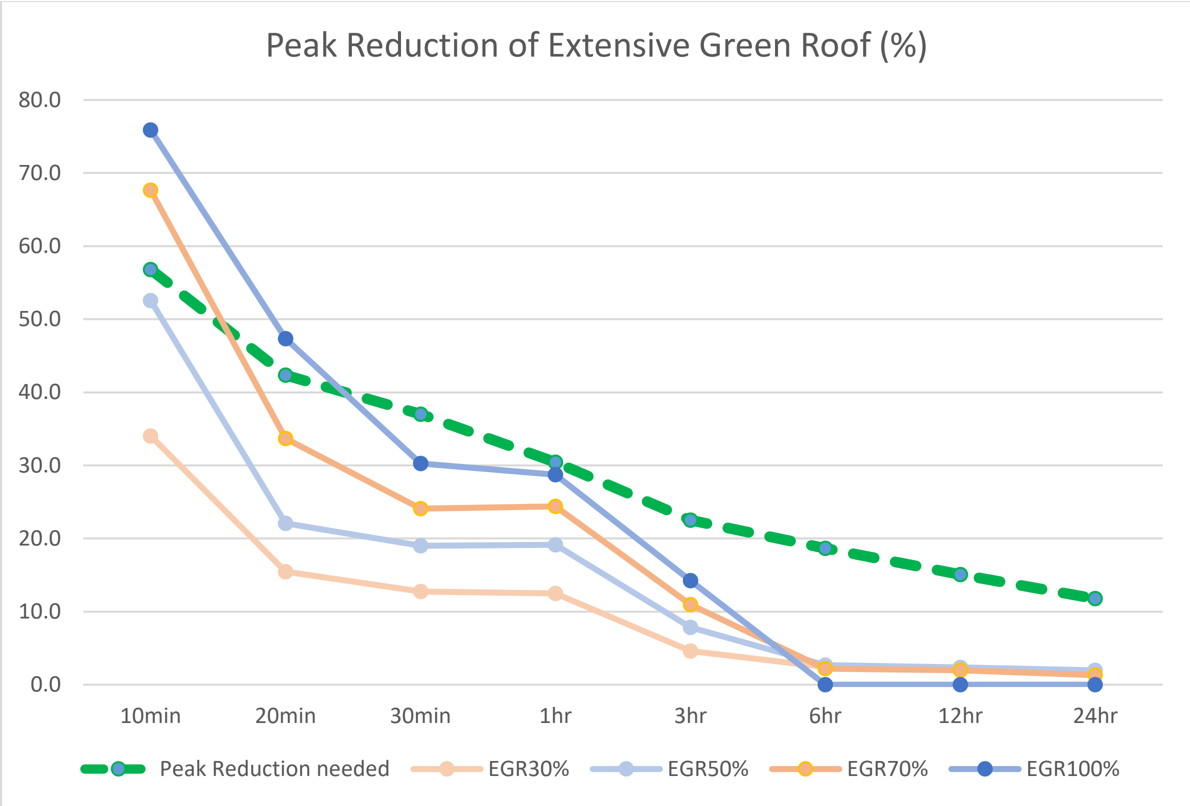

Figure 4.5: Peak Reduction graph for Extensive Green Roof scenarios across different design storm durations (CN70)

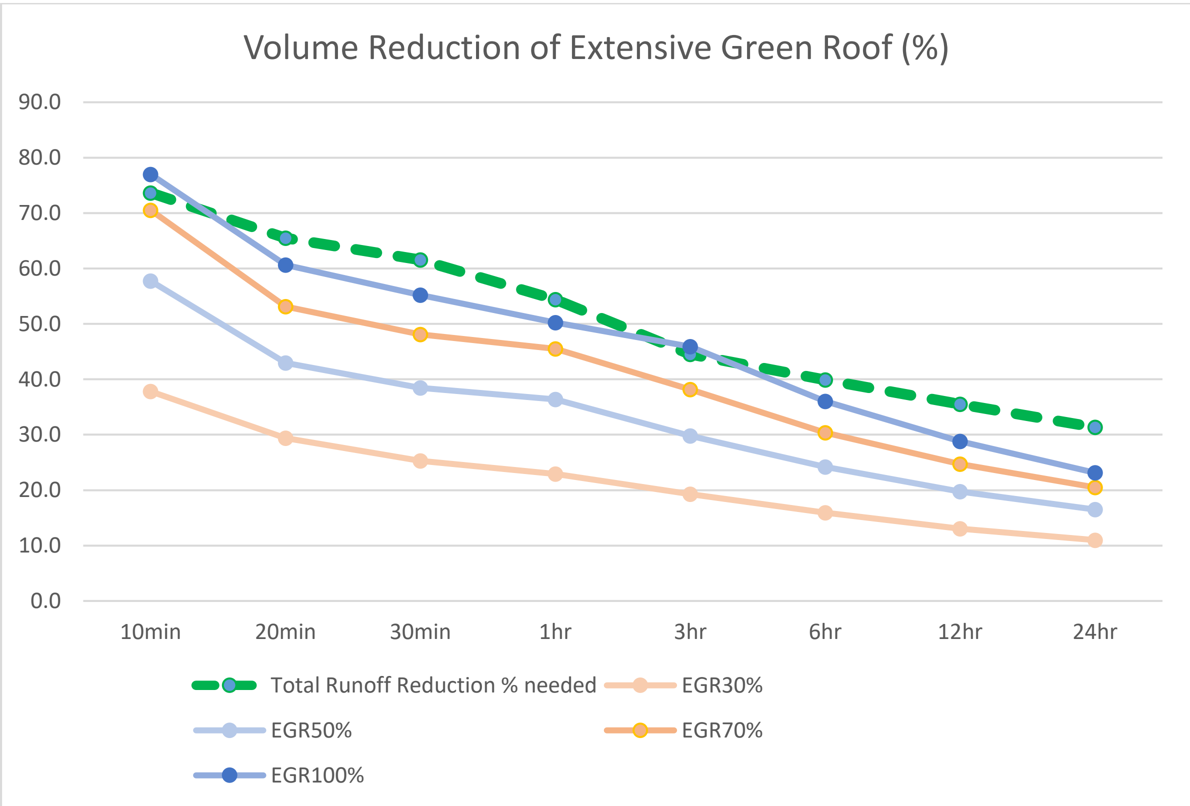

Figure 4.6: Total Volume Reduction graph for Extensive Green Roof scenarios across different design storm durations (CN70)

The Peak Reduction of the Extensive Green Roof (Figure 4.5) exhibits a steep downward trend as the design storm duration progresses to longer durations. For example, with the 10-minute storm, 100% coverage scenario shows 75.9% reduction in peak discharge, achieving Hydraulic Invariance. There are two other scenarios in which an Extensive Green Roof achieves Hydraulic Invariance; however, there is a critical failure point at the 6-hour rainfall duration, after which the Peak Reduction percentage drops to very low values (near zero). This behavior is the exact opposite of the Bioretention Cell behavior, which was able to recover during longer durations. The performance flat line, which happens after the 6-hour mark, shows that the Extensive Green Roof gets totally saturated in storms longer than 6-hours, and without more soil depth to buffer continued rainfall, it fails to absorb rainwater while at the same time draining slowly. This can explain why, during longer storms, lower coverages of Extensive Green Roof performed better (although the difference in performance is very limited).

The Volume Reduction (Figure 4.6) of the Extensive Green Roof follows a similar decline pattern, while even with 100% coverage, it mostly fails to achieve Hydrological Invariance.

4.3 Benchmarking (300 sqm Comparison)

By comparing three different types of LID Control discussed above, we can establish the efficiency gap. In order to compare the performance, we use the results achieved by the same coverage area; this normalized area of 300 sqm is equivalent to coverage in BR100%, PP50%, and EGR50% scenarios.

Table 4.7: Peak Discharge (LPS) for three LID Control types with 300 sqm of coverage (CN70), Shaded cells indicate compliance with HHI requirements ($Q_{Peak,LID} \leq Q_{Peak,Pre}$)

scenario	10min	20min	30min	1hr	3hr	6hr	12hr	24hr
natural	20.15	17.64	14.77	10.15	5.23	3.36	2.14	1.35
urbanized	46.65	30.6	23.45	14.59	6.75	4.13	2.52	1.53
BR100%	5.84	5	4.16	2.85	1.46	0.94	0.6	0.38
PP50%	22.13	16.42	13.18	8.61	6.27	3.92	2.36	1.4
EGR50%	22.13	23.84	18.99	11.8	6.22	4.02	2.46	1.5

Table 4.8: Total Volume (Liters) for three LID Control types with 300 sqm of coverage (CN70), Shaded cells indicate compliance with HHI requirements ($V_{Total,LID} \leq V_{Total,Pre}$)

scenario	10min	20min	30min	1hr	3hr	6hr	12hr	24hr
natural	7044	11470	14480	21330	35790	47700	62540	81310
urbanized	26740	33250	37660	46790	64520	79350	96940	118420
BR100%	2170	3300	4140	5980	10020	13360	17510	22770
PP50%	11300	14980	17790	23180	37920	51590	66930	83900
EGR50%	11300	18960	23180	29780	45310	60140	77780	98880

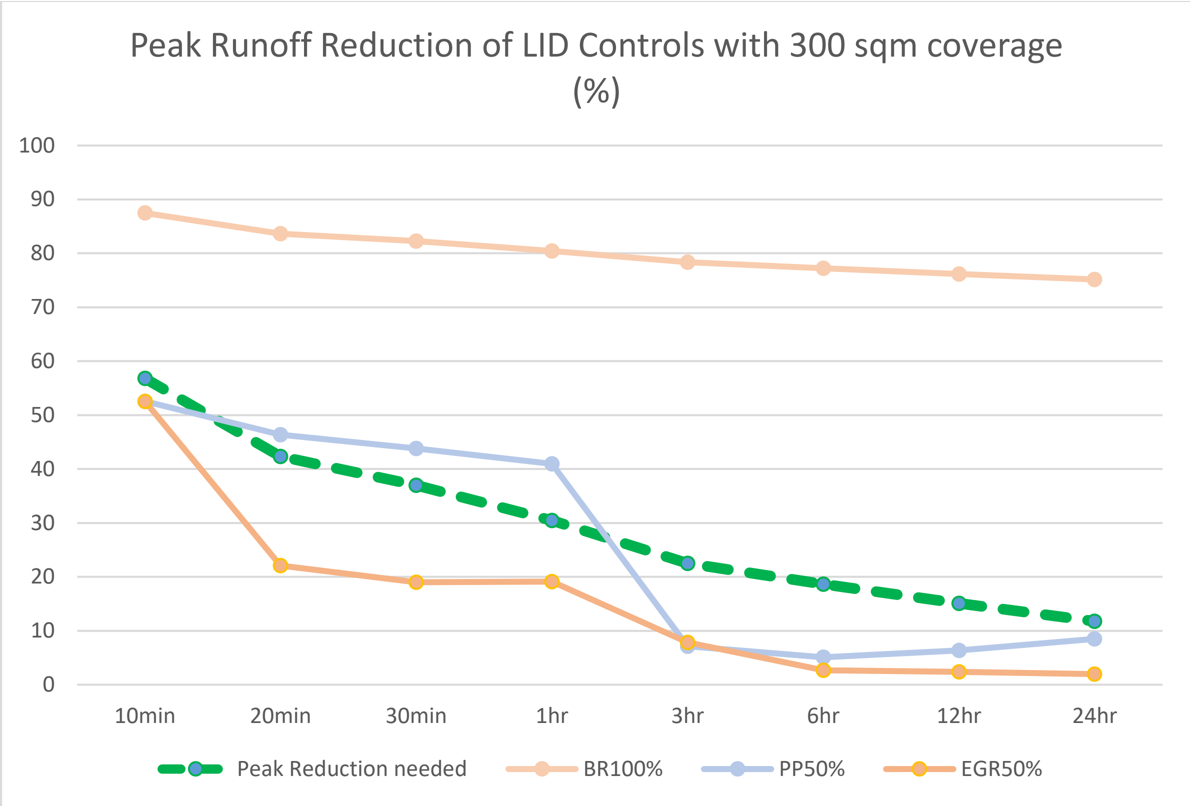

Figure 4.7: Peak Reduction graph for three LID Control types with 300 sqm of coverage scenarios across different design storm durations (CN70)

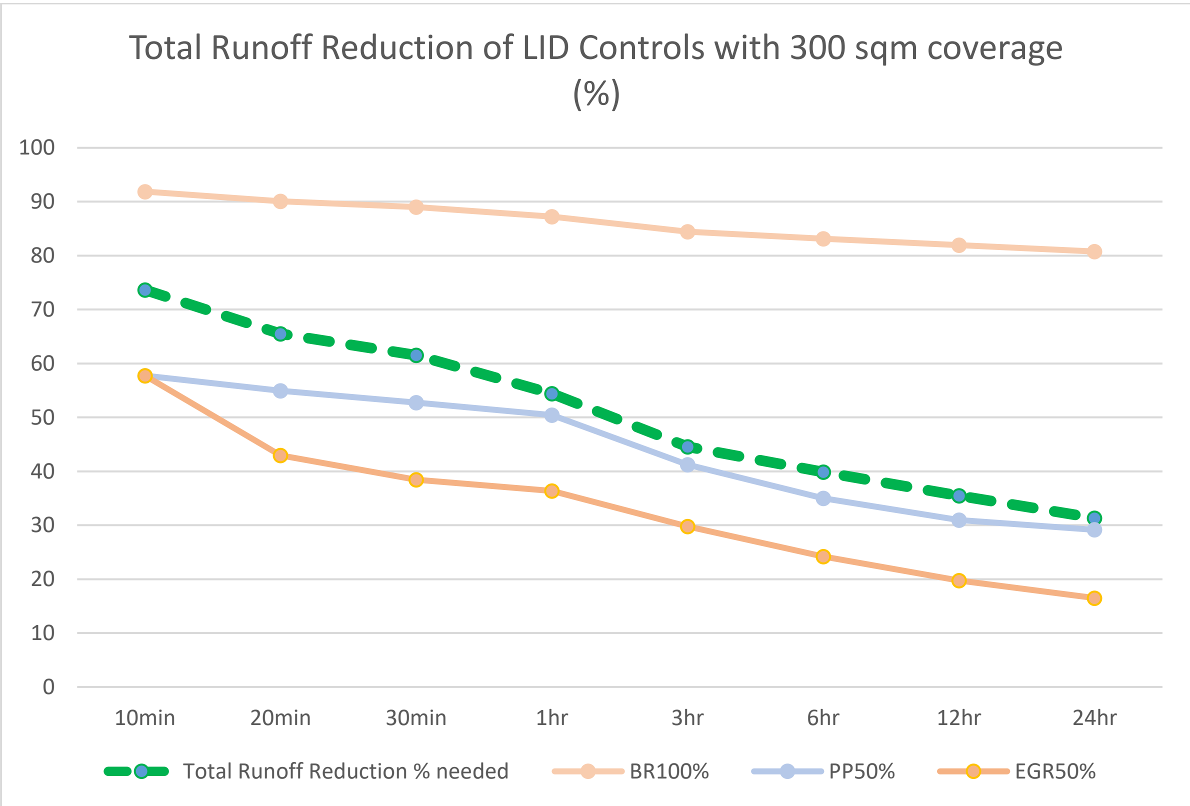

Figure 4.8: Total Volume Reduction graph for three LID Control types with 300 sqm of coverage scenarios across different design storm durations (CN70)

4.3.1 Peak Runoff Reduction Comparison

For the highest intensity and shortest design storm duration (10-minutes), both Permeable Pavement and Extensive Green Roof exhibit the same behavior and results in reduction (52.5%), which is very close to achieving Hydraulic Invariance. This, along with the same results for their Volume Reduction, shows that during very short intense rainfalls, both LID types function through their initial abstraction, capturing the same volume of runoff before their specific internal drainage characteristics start to make a difference during longer duration rainfalls. In the case of the Permeable Pavement, there is a sharp descent in the Peak Reduction performance after the 1-hour mark, at which it falls from 41% in 1-hour to 7% in 3-hours, only to recover by a small margin after 12-hours mark and finally finishing with 8.5% in 24-hours. This shows that its shallow storage layer offers limited buffering capacity and recovery during longer duration rainfalls with lower intensity, while it is more effective at reducing the peak discharge during shorter and more intense rainfalls. The Extensive Green Roof exhibits an even sharper decline in Peak Reduction after the 1-hour mark, falling to 7% in 3-hours before losing almost all of its capacity in Peak Reduction for longer rainfall durations.

With 300 sqm of coverage area, the Bioretention Cell remains by a big margin the best performing of these three LID types; its Peak Reduction ranges between 87.5% and 75% during different design storm durations, remaining well above the Peak Reduction needed to achieve Hydraulic Invariance.

4.3.2 Total Runoff Reduction Comparison

The Volume Reduction results (Figure 4.8) from the simulations confirm the volumetric limitations of shallow LID Controls. It can be observed that for the Permeable Pavement and the Extensive Green Roof, 300 sqm of coverage is not enough to achieve Hydrological Invariance in the 1000 sqm case study plot. Contrary to the results from the other two types of LID Control, the Bioretention Cell shows a robust retention capacity. It easily achieves Hydrological Invariance in all rainfall durations with Volume Reduction ranging from 92% in 10-minutes, and 81% in 24-hours. This is a direct result of its 1000 mm total depth, which allows for a much higher retention volume availability when compared to the other two LID Controls, which have much shallower profiles and get saturated more easily.

4.3.3 Viability

The benchmarking results present a clear technical paradox, while it is clear that with the same coverage area, the Bioretention Cell has a superior performance in reducing both peak discharge and total runoff volume compared to the other two LID Control types, it has an important limitation in terms of spatial costs. The Bioretention Cell needs to be implemented on a ground-level pervious area, which is a luxury rarely available in dense urban developments. As a standalone solution, the Bioretention Cell needs a substantial coverage area and ends up competing with the building footprint as it completely changes the land use in its area of implementation. This fact makes it a less viable option when compared to the other two types of LID Controls. In comparison, the Permeable Pavement does not have the same problem and can be effective in an urban development with a large area in need of paving; however, it fails to have a meaningful effect on HHI achievement if it covers a small portion of the site area. In the case of the Extensive Green Roof, while it is the least efficient performer of the three LID Control types, it is the most spatially viable option as it occupies the building's roof, a surface with zero spatial cost.

This analysis concludes that, in order for ground-level LID Controls, such as Bioretention Cells and Permeable Pavement, to be effective, they require large coverage areas in the case study plot. However, since the land value is usually at a premium, the next logical step in this study is to investigate if a high-performance Intensive Green Roof can effectively bridge the performance gap between the spatially viable Extensive Green Roof and the superior performing Bioretention Cell.

4.4 Intensive Green Roof

The Intensive Green Roof was modeled with 500 mm of soil thickness and 50 mm of berm height; compared to the Extensive Green Roof, these physical upgrades transform the Green Roof from being a simple vegetative cover into a high-capacity detention and retention unit. In this section, the results for simulations of the Intensive Green Roof scenarios with a native soil of hydrologic soil group C (CN70) are presented in order to have a better understanding of how its performance compares to EGR and other types of LID Controls.

Table 4.9: Peak Discharge (LPS) for Intensive Green Roof (CN70), Shaded cells indicate compliance with HHI requirements ($Q_{Peak,LID} \leq Q_{Peak,Pre}$)

scenario	10min	20min	30min	1hr	3hr	6hr	12hr	24hr
natural	20.15	17.64	14.77	10.15	5.23	3.36	2.14	1.35
urbanized	46.65	30.6	23.45	14.59	6.75	4.13	2.52	1.53
IGR30%	30.77	21.55	16.94	10.84	5.15	3.2	1.97	1.21
IGR50%	22.13	16.42	13.18	8.61	4.18	2.62	1.63	1.01
IGR70%	15.09	12.05	9.89	6.62	3.29	2.08	1.31	0.81
IGR100%	7.45	6.85	5.82	4.04	2.09	1.34	0.85	0.54

Table 4.10: Total Volume (Liters) for Intensive Green Roof (CN70), Shaded cells indicate compliance with HHI requirements ($V_{Total,LID} \leq V_{Total,Pre}$)

scenario	10min	20min	30min	1hr	3hr	6hr	12hr	24hr
natural	7044	11470	14480	21330	35790	47700	62540	81310
urbanized	26740	33250	37660	46790	64520	79350	96940	118420
IGR30%	16630	21360	24800	31500	45630	57100	70960	88160
IGR50%	11300	14980	17790	23180	34820	44280	55760	70210
IGR70%	7080	9830	11980	16200	25430	32990	42220	54040
IGR100%	2710	4310	5530	8520	14020	19090	25090	33150

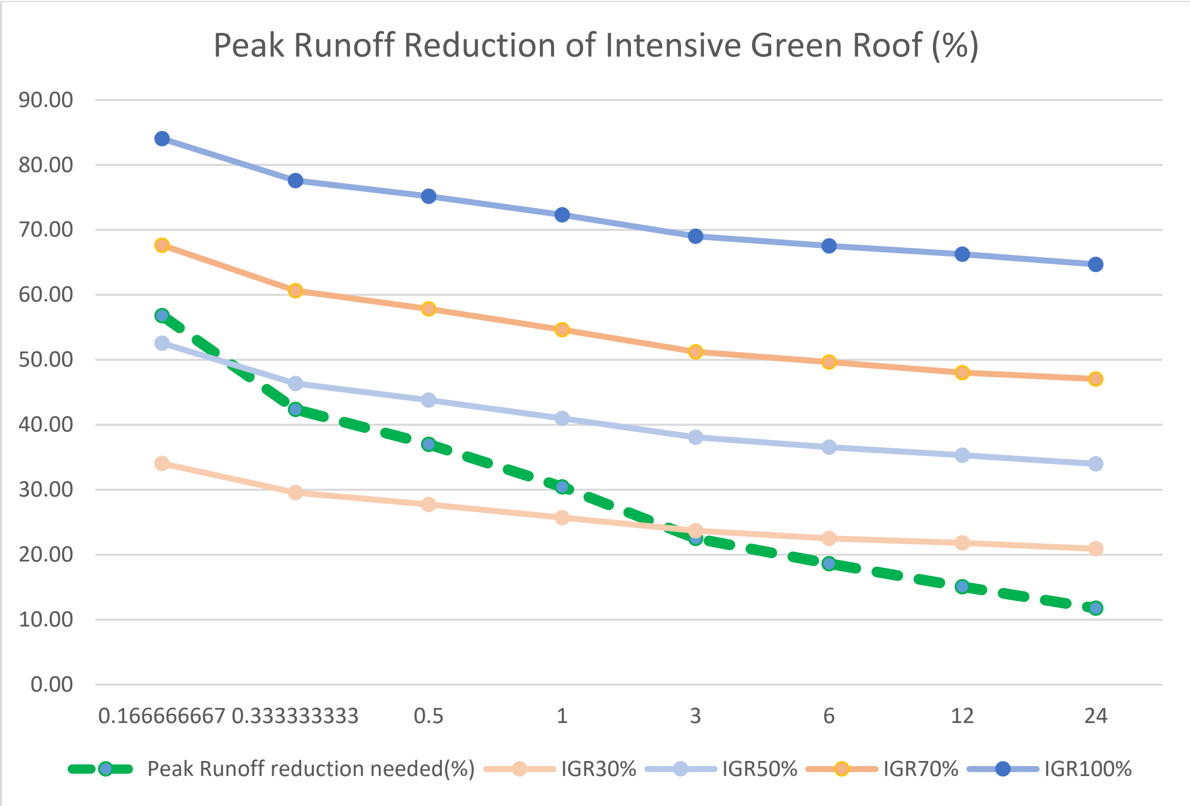

Figure 4.9: Peak Reduction graph for Intensive Green Roof scenarios across different design storm durations (CN70)

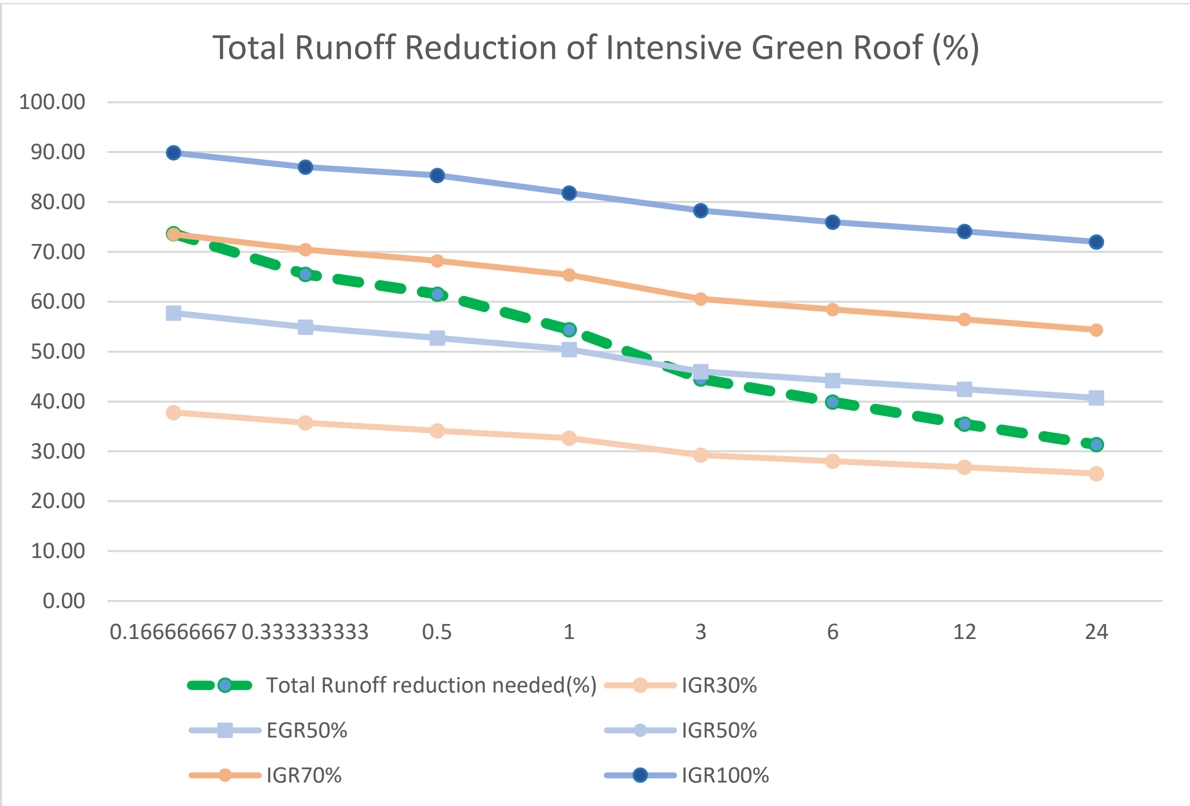

Figure 4.10: Total Volume Reduction graph for Intensive Green Roof scenarios across different design storm durations (CN70)

In comparison to the Extensive Green Roof, the Intensive Green Roof shows a more robust Peak Reduction performance (Figure 4.9) across all rainfall durations. While the Extensive Green Roof showed a steep decline in performance during the longer design storm durations, the Intensive Green Roof shows a more stable potential in reducing peak discharge with coverages 50% and higher, achieving Hydraulic Invariance in all but one simulated instance. In comparison, even 30% coverage is able to achieve Hydraulic Invariance during rainfalls longer than 3-hours. Additionally, unlike the Extensive Green Roof, there is a pronounced difference between the performance of different coverages, with higher coverages showing more peak reduction. This is caused by 500 mm of soil depth, which acts as a significant buffer to delay the discharge of the absorbed water far beyond the critical timing of the design storm peak.

The Volume Reduction graph of the Intensive Green Roof (Figure 4.10) also highlights a superior performance compared to the Extensive Green Roof. The IGR100% achieves Hydrological Invariance in all durations, with the Volume Reduction ranging from 90% in 10-minutes duration, to 72% in 24-hours. While lower coverages also show significant improvements over the Extensive Green Roof, with IGR70% only failing in 10-minutes duration, and IGR50% achieving the Hydrological Invariance during four longer durations.

4.5 Green Roof Variants Sensitivity to Native Soil Conditions

The previous section showed the superiority of the Intensive Green Roof over the Extensive Green Roof under standard conditions of previous simulations (CN70). However, the regulatory requirements for the Hydraulic and Hydrological Invariance (HHI) are relative targets, meaning that they are defined by the difference between pre-development and post-development states in a given site, and a greater increase in runoff in the post-development state means more intervention is needed to restore the natural pre-development runoff values.

This section explores the role of the local geology on the effectiveness of the Green Roof variants. By varying the native Curve Number (CN) from 35 (highly permeable sand) to 77 (clay with low permeability), this analysis identifies the HHI threshold for each soil type. This sensitivity analysis is crucial in order to understand whether a lightweight EGR can achieve HHI in a given soil type, or a heavier IGR is needed to compensate for the negative effects on runoff generation caused by development.

4.5.1 Performance on Soil Group A (CN 35)

The simulation results for CN35 present the most challenging scenarios for achieving HHI. As the native soil, which has a high infiltration capacity, is covered with an impervious surface in the post-development scenario, returning the equilibrium to the natural (pre-development) state is a more challenging task.

Table 4.11: Peak Discharge (LPS) for Extensive and Intensive Green Roof (CN35), Shaded cells indicate compliance with HHI requirements ($Q_{Peak,LID} \leq Q_{Peak,Pre}$)

scenario	10min	20min	30min	1hr	3hr	6hr	12hr	24hr
natural	4.13	4.79	4.55	3.56	2.1	1.46	1	0.68
urbanized	40.63	25.51	19.36	11.95	5.5	3.37	2.06	1.27
EGR30%	24.02	19.4	15.54	9.65	4.91	3.13	1.93	1.19
EGR50%	15.25	16.8	13.86	8.58	4.63	3.09	1.9	1.18
EGR70%	8.34	13.4	12.76	7.9	4.46	3.13	1.93	1.19
EGR100%	12.06	10.3	12.12	7.6	4.49	3.37	2.07	1.27
IGR30%	24.02	15.59	12.09	7.7	3.66	2.29	1.43	0.89
IGR50%	15.25	10.29	8.18	5.38	2.65	1.69	1.07	0.68
IGR70%	8.34	6.09	5.03	3.48	1.8	1.18	0.76	0.5
IGR100%	1.43	1.77	1.73	1.4	0.84	0.58	0.4	0.27

Table 4.12: Total Volume (Liters) for Extensive and Intensive Green Roof (CN35), Shaded cells indicate compliance with HHI requirements ($V_{Total,LID} \leq V_{Total,Pre}$)

scenario	10min	20min	30min	1hr	3hr	6hr	12hr	24hr
natural	1410	2590	3600	5930	11450	17540	24210	33300
urbanized	24520	29870	33450	40540	55000	66920	81610	99250
EGR30%	14160	18950	22290	27910	40570	52190	65820	82570
EGR50%	8800	13300	16480	21460	33370	44640	58530	75200
EGR70%	6150	8850	12450	17130	28310	39660	54060	71020
EGR100%	4100	6480	9670	13330	24280	37250	52630	70620
IGR30%	14160	17500	19810	24490	34230	42500	52830	65370
IGR50%	8800	11040	12640	15970	23050	29230	37070	46730
IGR70%	4610	5980	7000	9190	14030	18390	24080	31250
IGR100%	490	930	1320	2260	4500	6660	9770	13980

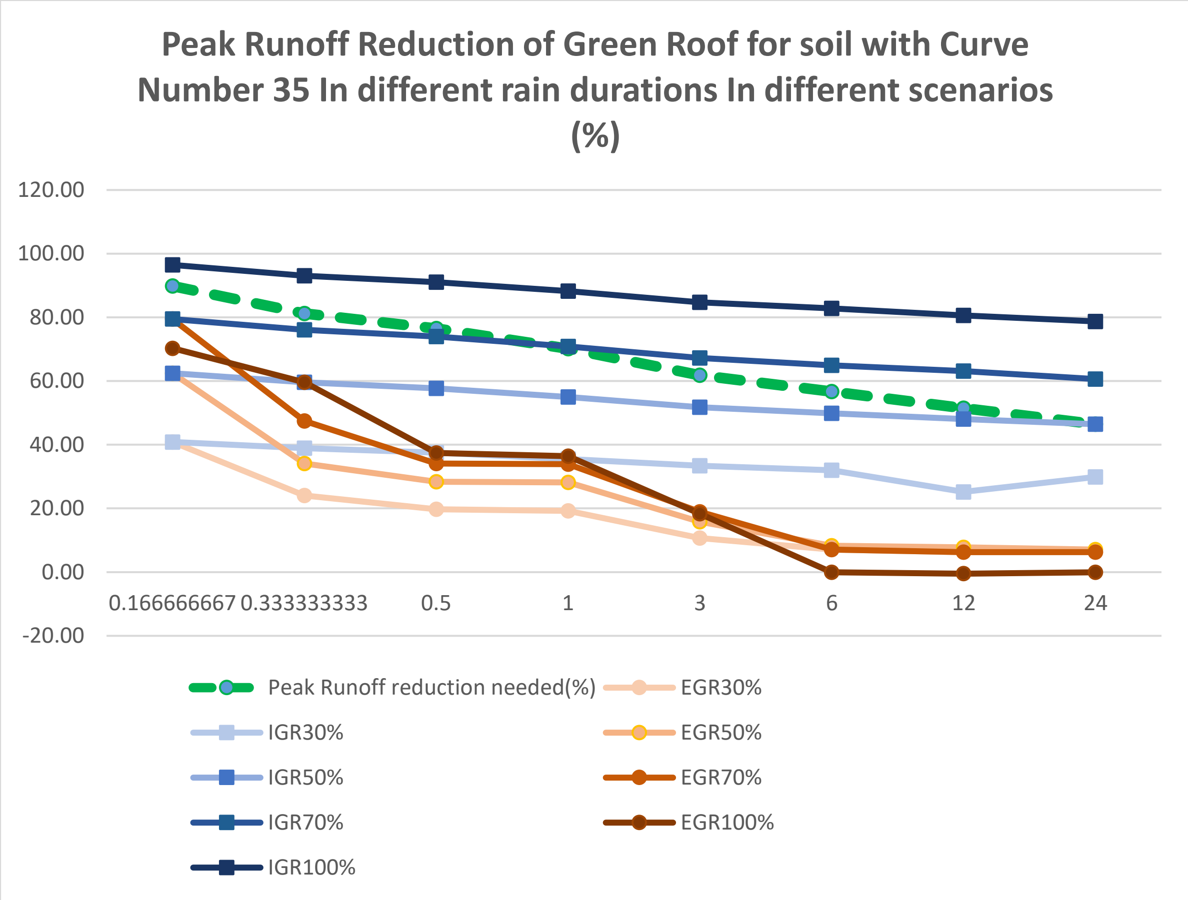

Figure 4.11: Peak Reduction graph for Extensive and Intensive Green Roof scenarios across different design storm durations (CN35)

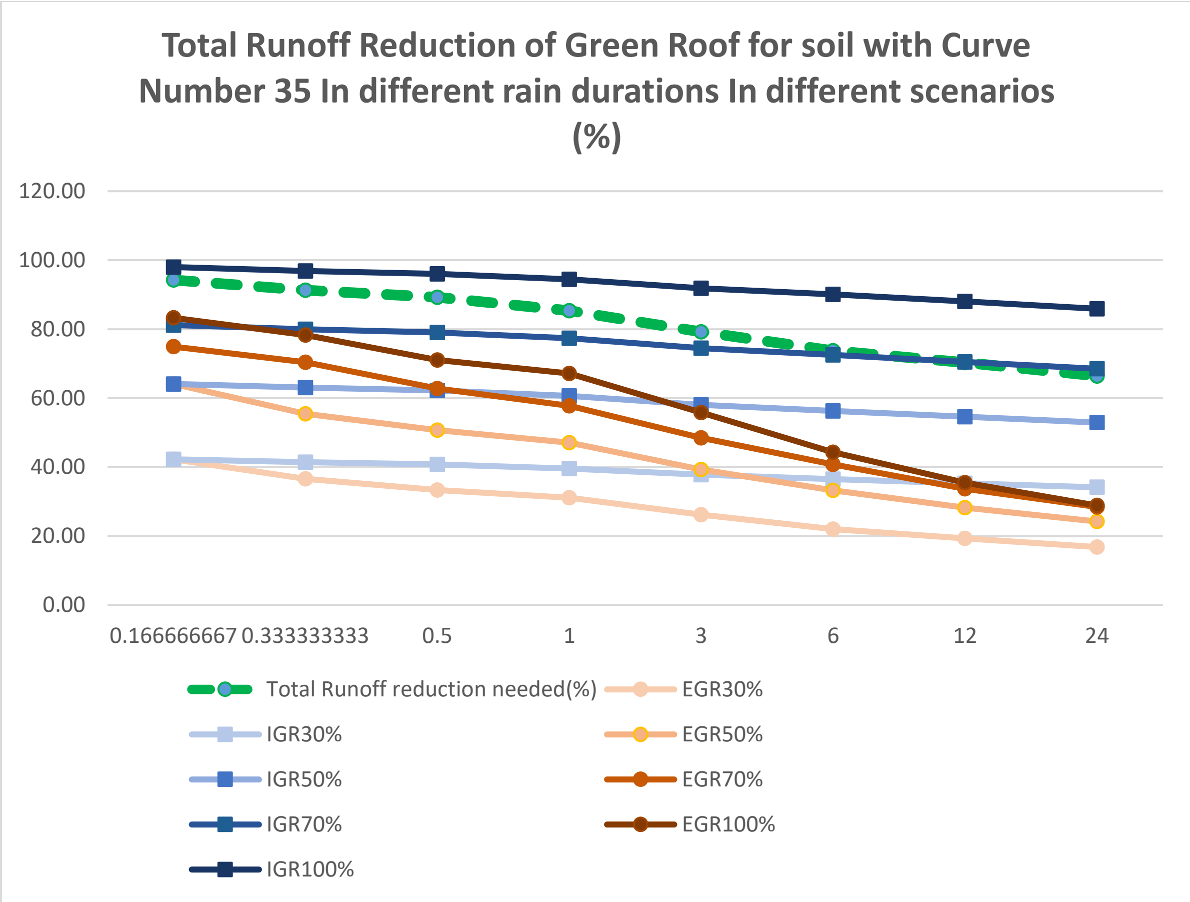

Figure 4.12: Total Volume Reduction graph for Extensive and Intensive Green Roof scenarios across different design storm durations (CN35)

The results reveal that, compared to CN70 in CN35, the target line for both Peak Reduction and Volume Reduction is much higher as a result of higher infiltration of CN35. This also highlights the performance difference between IGR and EGR, as EGR fails to achieve the Hydraulic and Hydrological Invariance in every scenario, regardless of the coverage. IGR is able to reach Hydraulic Invariance with 100% coverage (IGR100%) in all durations, and in longer durations with lower coverages. However, as it is only able to reduce the total runoff volume to the pre-development values with 100% coverage (IGR100%) in all design storm durations, it is safe to say that to satisfy the HHI requirements in CN35, we need to implement 100% coverage of the roof by IGR. It should be noted that the HHI is also achieved by IGR70% in 12-hour and 24-hour rainfall durations, but not in other durations.

4.5.2 Performance on Soil Group B (CN 56)

Table 4.13: Peak Discharge (LPS) for Extensive and Intensive Green Roof (CN56), Shaded cells indicate compliance with HHI requirements ($Q_{Peak,LID} \leq Q_{Peak,Pre}$)

scenario	10min	20min	30min	1hr	3hr	6hr	12hr	24hr
natural	11.32	11.09	9.72	7.03	3.84	2.56	1.68	1.09
urbanized	43.28	27.98	21.42	13.34	6.19	3.81	2.34	1.43
EGR30%	26.94	22.59	18.03	11.29	5.77	3.65	2.25	1.39
EGR50%	18.22	20.32	16.47	10.27	5.52	3.62	2.24	1.38
EGR70%	11.26	16.86	15.33	9.54	5.33	3.65	2.25	1.39
EGR100%	9.62	13.23	14.28	8.98	5.21	3.81	2.34	1.43
IGR30%	26.94	18.45	14.52	9.34	4.49	2.81	1.75	1.09
IGR50%	18.22	13.23	10.69	7.07	3.5	2.23	1.4	0.88
IGR70%	11.26	8.95	7.47	5.12	2.63	1.7	1.09	0.69
IGR100%	4.08	4.23	3.79	2.79	1.53	1.02	0.67	0.44

Table 4.14: Total Volume (Liters) for Extensive and Intensive Green Roof (CN56), Shaded cells indicate compliance with HHI requirements ($V_{Total,LID} \leq V_{Total,Pre}$)

scenario	10min	20min	30min	1hr	3hr	6hr	12hr	24hr
natural	4020	6630	8680	13120	23700	32910	44570	59780
urbanized	25470	31390	35410	43360	59970	73440	89750	109850
EGR30%	15200	20860	24850	31550	46300	59500	75690	95140
EGR50%	9850	15670	19630	25840	39510	52800	68900	88190
EGR70%	6490	11850	15650	20880	33980	47590	64160	83750
EGR100%	4320	9630	12950	17250	29660	44320	61450	81500
IGR30%	15200	19220	22050	27790	40230	50240	62510	77880
IGR50%	9850	12790	14930	19380	29250	37210	47050	59620
IGR70%	5650	7690	9240	12490	20030	26130	33760	43770
IGR100%	1430	2450	3280	5080	9470	13170	17910	24570

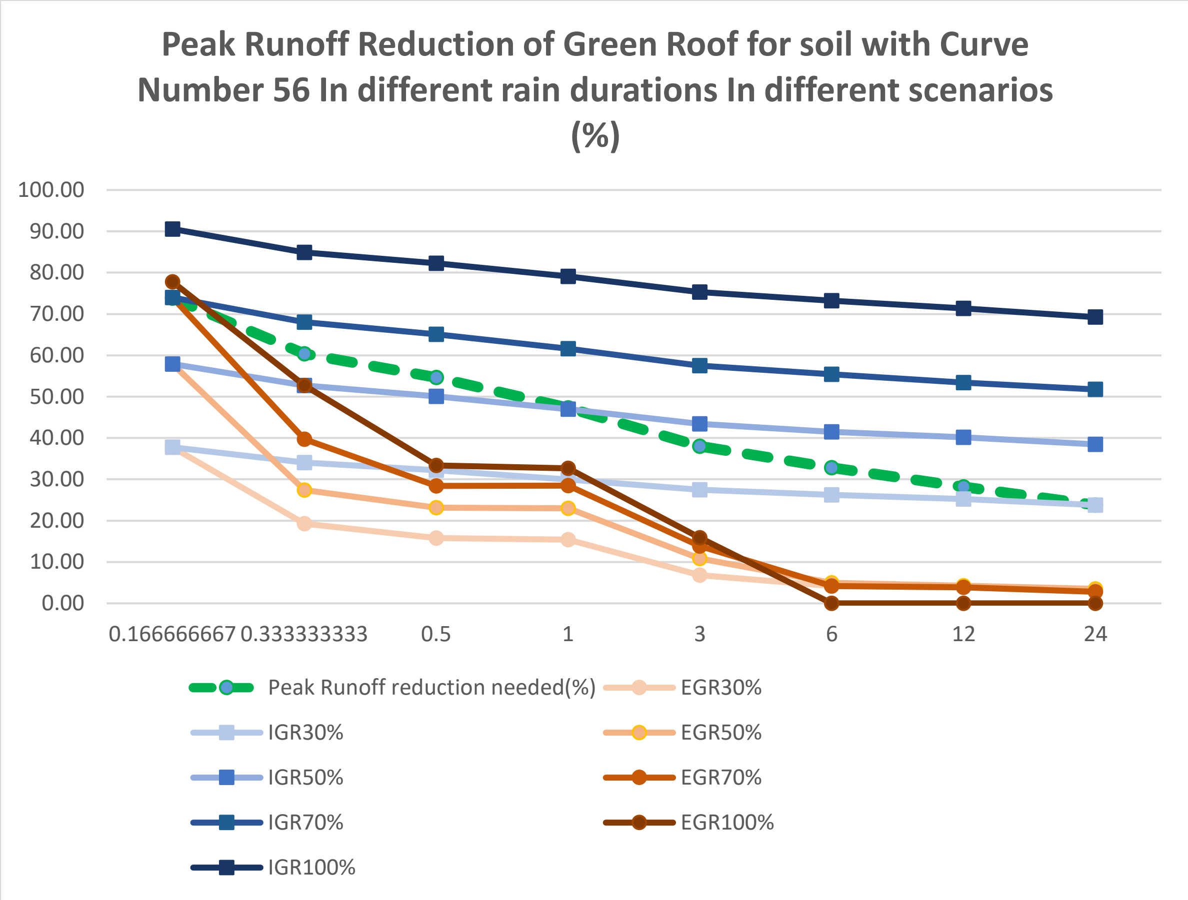

Figure 4.13: Peak Reduction graph for Extensive and Intensive Green Roof scenarios across different design storm durations (CN56)

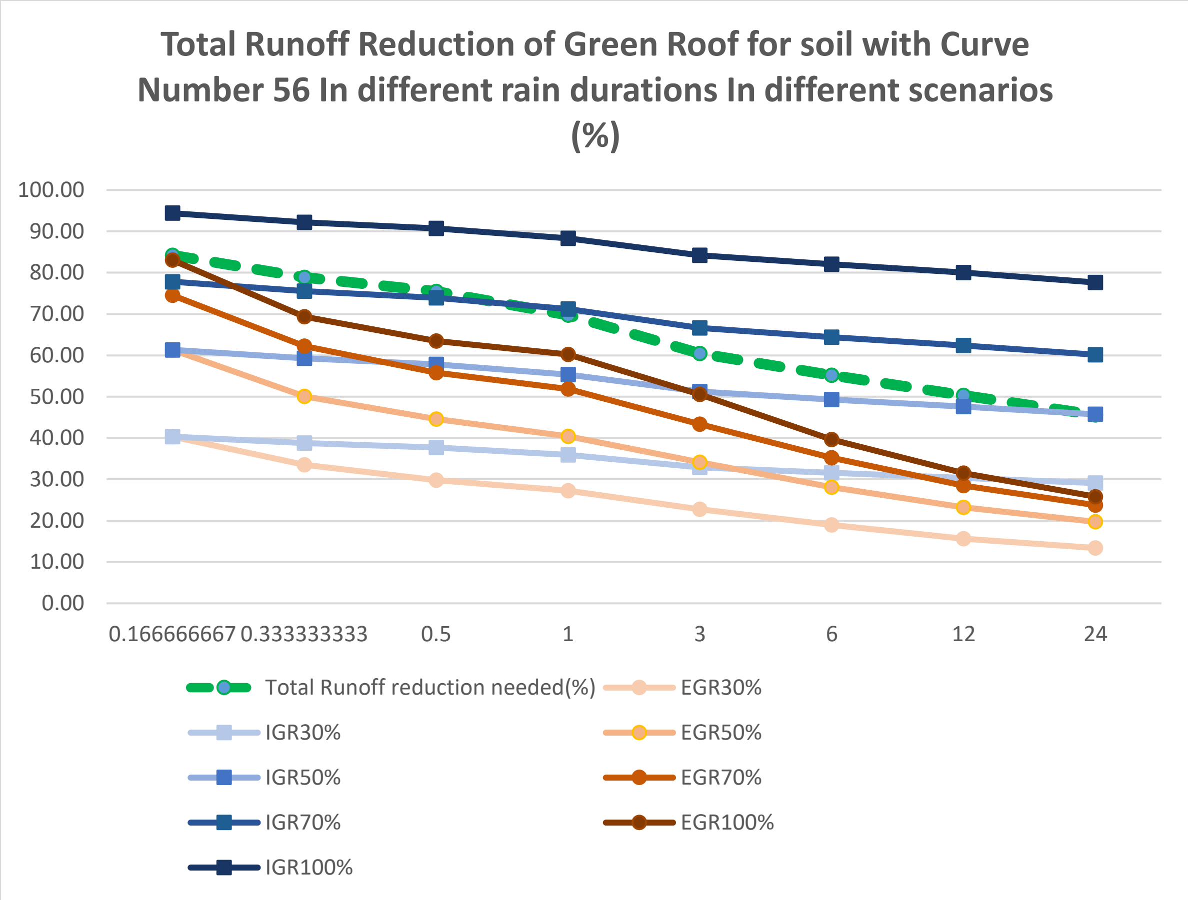

Figure 4.14: Total Volume Reduction graph for Extensive and Intensive Green Roof scenarios across different design storm durations (CN56)

The results from the simulations run with native soil with Curve Number 56 (CN56), reveal that due to higher runoff coefficient of this soil compared to CN35 the site's response in natural state is different, as a result of higher runoff caused by this, the targets for Peak Reduction and Volume Reduction are lower, although they remain higher than the values observed in CN70.

The Peak Reduction graph (Figure 4.13) shows the beginning of full compliance of IGR70% across all durations, as well as IGR50% achieving Hydraulic Invariance in durations longer than 3 hours. The Extensive Green Roofs still lack full compliance with EGR100% and EGR70%, achieving the Hydraulic Invariance only in 10-minutes duration, after which they also decline to much lower values.

The Extensive Green Roof fails to achieve the Hydrological Invariance in any simulated instant. The Intensive Green Roof is more successful with IGR100%'s compliance in all durations, and IGR70% and IGR50% partial compliance (Figure 4.14).

4.5.3 Performance on Soil Group C (CN 70)

Table 4.15: Peak Discharge (LPS) for Extensive and Intensive Green Roof (CN70), Shaded cells indicate compliance with HHI requirements ($Q_{Peak,LID} \leq Q_{Peak,Pre}$)

scenario	10min	20min	30min	1hr	3hr	6hr	12hr	24hr
natural	20.15	17.64	14.77	10.15	5.23	3.36	2.14	1.35
urbanized	46.65	30.6	23.45	14.59	6.75	4.13	2.52	1.53
EGR30%	30.77	25.87	20.46	12.77	6.44	4.03	2.47	1.51
EGR50%	22.13	23.84	18.99	11.8	6.22	4.02	2.46	1.5
EGR70%	15.09	20.3	17.8	11.03	6.01	4.04	2.47	1.51
EGR100%	11.24	16.12	16.35	10.4	5.79	4.13	2.52	1.53
IGR30%	30.77	21.55	16.94	10.84	5.15	3.2	1.97	1.21
IGR50%	22.13	16.42	13.18	8.61	4.18	2.62	1.63	1.01
IGR70%	15.09	12.05	9.89	6.62	3.29	2.08	1.31	0.81
IGR100%	7.45	6.85	5.82	4.04	2.09	1.34	0.85	0.54

Table 4.16: Total Volume (Liters) for Extensive and Intensive Green Roof (CN70), Shaded cells indicate compliance with HHI requirements ($V_{Total,LID} \leq V_{Total,Pre}$)

scenario	10min	20min	30min	1hr	3hr	6hr	12hr	24hr
natural	7044	11470	14480	21330	35790	47700	62540	81310
urbanized	26740	33250	37660	46790	64520	79350	96940	118420
EGR30%	16630	23470	28140	36060	52090	66700	84270	105410
EGR50%	11300	18960	23180	29780	45310	60140	77780	98880
EGR70%	7880	15580	19540	25500	39900	55240	72980	94150
EGR100%	6150	13080	16870	23290	34920	50740	69010	91020
IGR30%	16630	21360	24800	31500	45630	57100	70960	88160
IGR50%	11300	14980	17790	23180	34820	44280	55760	70210
IGR70%	7080	9830	11980	16200	25430	32990	42220	54040
IGR100%	2710	4310	5530	8520	14020	19090	25090	33150

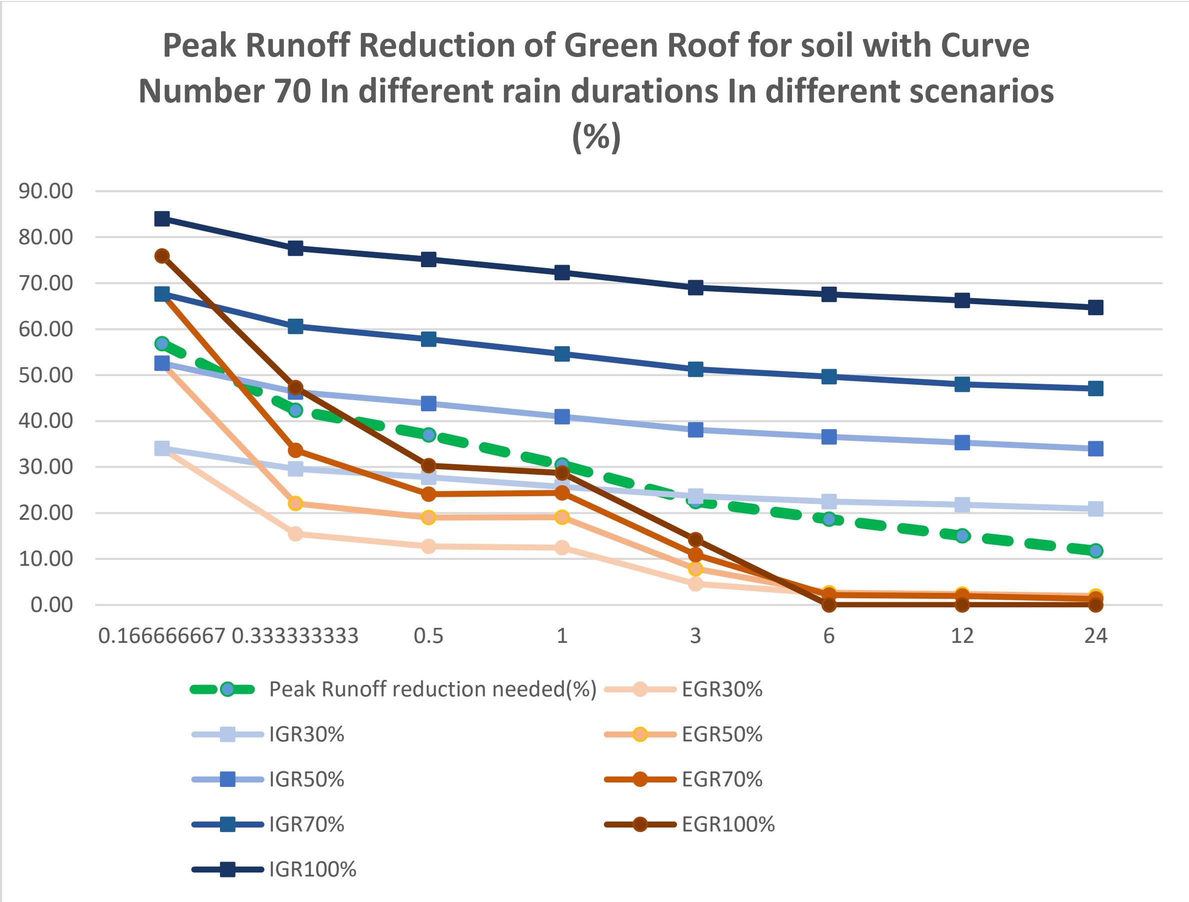

Figure 4.15: Peak Reduction graph for Extensive and Intensive Green Roof scenarios across different design storm durations (CN70)

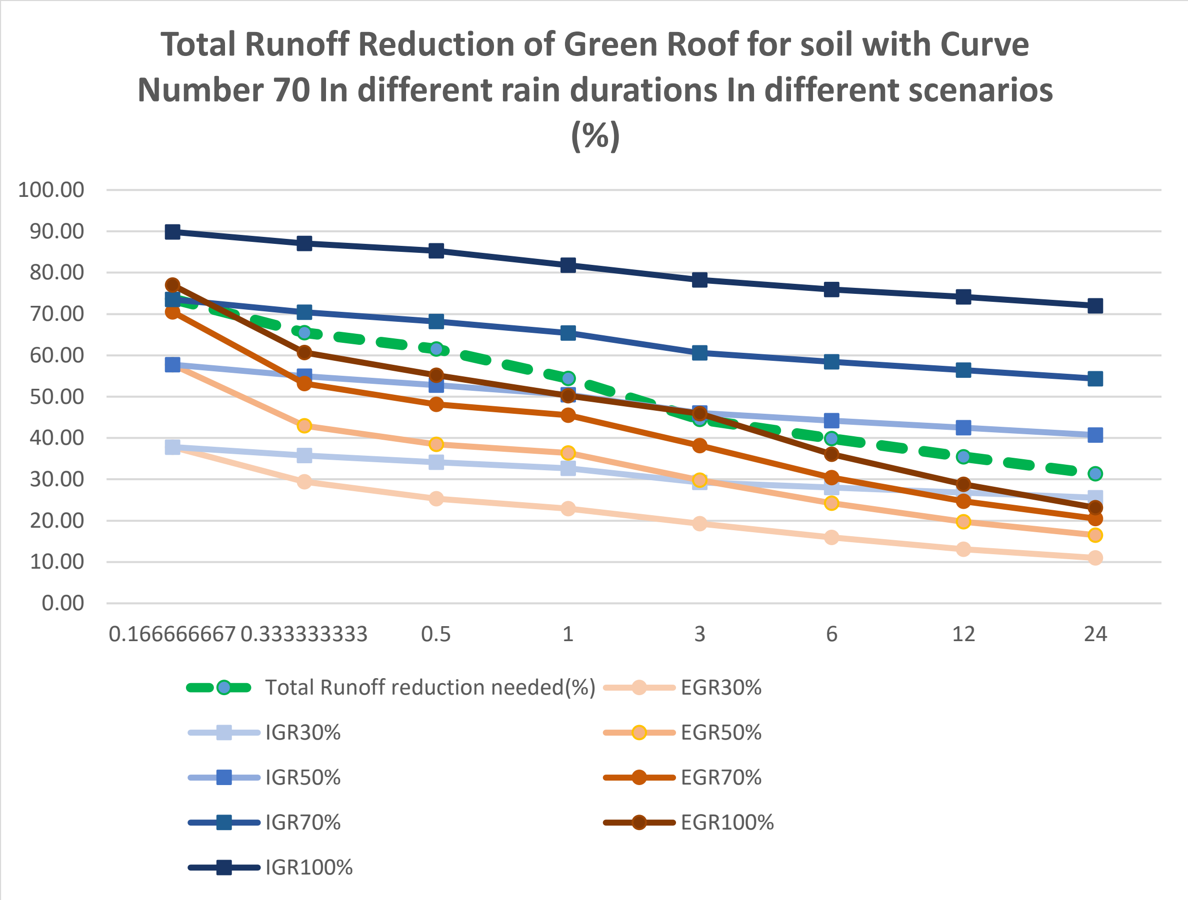

Figure 4.16: Total Volume Reduction graph for Extensive and Intensive Green Roof scenarios across different design storm durations (CN70)

4.5.4 Performance on Soil Group D (CN 77)

The final section of the sensitivity analysis presents the results for simulations using Curve Number 77 (CN77) as the native soil, which was chosen to represent the lowest permeability conditions in the Piedmont region. When using CN77 as the native soil, the natural (pre-development) state is characterized by high runoff potential, resulting in HHI targets that are easiest to achieve in the entire study.

Table 4.17: Peak Discharge (LPS) for Extensive and Intensive Green Roof (CN77), Shaded cells indicate compliance with HHI requirements ($Q_{Peak,LID} \leq Q_{Peak,Pre}$)

scenario	10min	20min	30min	1hr	3hr	6hr	12hr	24hr
natural	26.77	22.01	17.98	12	5.96	3.77	2.35	1.46
urbanized	49.23	32.36	24.74	15.33	7.04	4.29	2.6	1.58
EGR30%	33.74	28.05	22	13.66	6.8	4.23	2.57	1.56
EGR50%	25.18	26.15	20.59	12.71	6.59	4.21	2.57	1.56
EGR70%	18.06	22.55	19.36	11.9	6.38	4.23	2.57	1.56
EGR100%	14.62	17.99	17.66	10.96	6.09	4.29	2.6	1.58
IGR30%	33.74	23.65	18.5	11.72	5.51	3.39	2.07	1.26
IGR50%	25.18	18.58	14.78	9.53	4.55	2.82	1.73	1.06
IGR70%	18.06	14.15	11.44	7.5	3.64	2.27	1.41	0.87
IGR100%	10.03	8.61	7.12	4.78	2.38	1.51	0.94	0.58

Table 4.18: Total Volume (Liters) for Extensive and Intensive Green Roof (CN77), Shaded cells indicate compliance with HHI requirements ($V_{Total,LID} \leq V_{Total,Pre}$)

scenario	10min	20min	30min	1hr	3hr	6hr	12hr	24hr
natural	10170	15100	19030	27370	43550	56830	73180	93560
urbanized	27780	34670	39700	48710	67710	82900	101190	123340
EGR30%	17800	26020	30480	38460	55840	71260	89370	111250
EGR50%	13170	21620	25940	33150	49380	64830	83120	104950
EGR70%	10470	18330	22530	28350	44150	59790	78250	100090
EGR100%	8620	15980	19130	23790	38770	54800	73570	95510
IGR30%	17800	23200	26780	34160	49420	61500	76060	94000
IGR50%	12500	16910	19800	25950	38720	48810	61010	76230
IGR70%	8250	11670	13960	18870	29220	37390	47310	59880
IGR100%	3740	5730	7570	10430	17210	22640	29350	38060

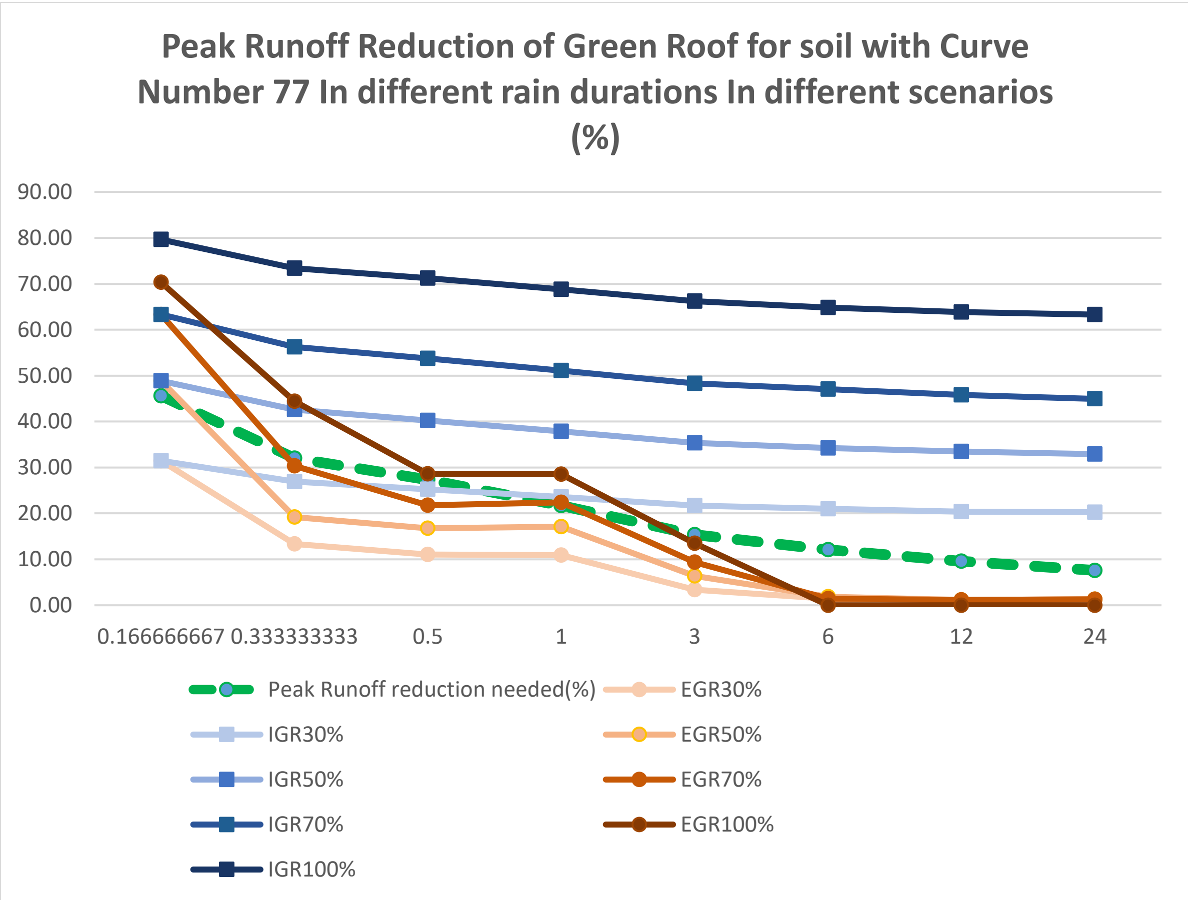

Figure 4.17: Peak Reduction graph for Extensive and Intensive Green Roof scenarios across different design storm durations (CN77)

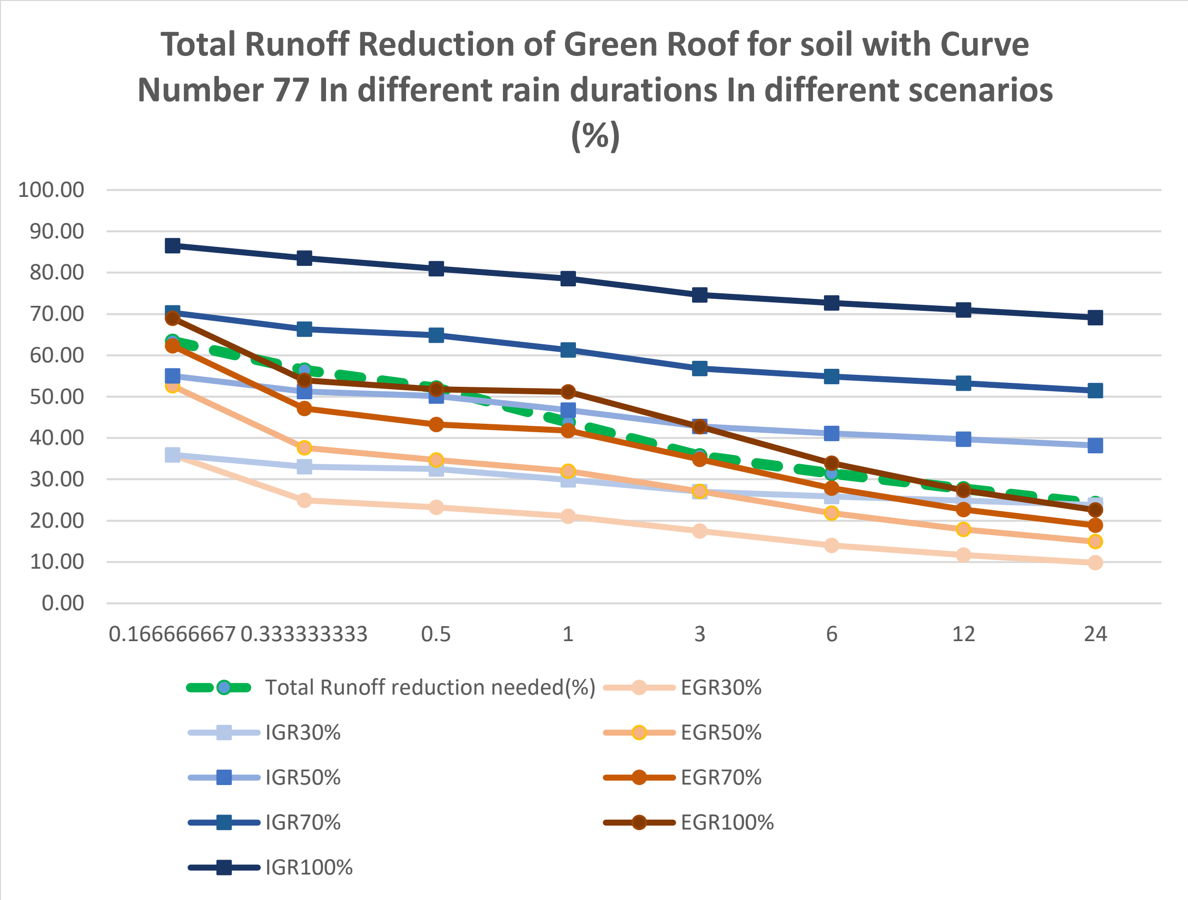

Figure 4.18: Total Volume Reduction graph for Extensive and Intensive Green Roof scenarios across different design storm durations (CN77)

Results of the simulations carried out with CN77 show that EGR100% is capable of achieving Hydraulic Invariance in short durations (under 1-hour), while also achieving in some durations of rainfall and closely following in other durations, the Volume Reduction needed for Hydrological Invariance. This highlights that EGR has some limited capacity in achieving HHI requirements during some specific conditions (native soil with low permeability and short-duration rainfalls). At the same time, the results exhibit high capabilities of IGR, with IGR100% and IGR70% satisfying both Peak and Volume Reduction needed for HHI in the entire range of rainfall durations. It should be noted that IGR simulation results show a massive reduction in the Peak Discharge, especially under longer-duration rainfalls, where the reduction is much more than needed.

4.6 Regional Application and HHI Maps

The final stage of this study translates the results obtained from the Green Roof simulations into a series of maps for better understanding and decision-making. These maps identify the minimum Green Roof (GR) configuration able to satisfy the HHI requirements for each design storm duration in different soil groups. The maps are divided into two different groups, with the first group illustrating the minimum Green Roof needed to achieve Hydraulic Invariance (achieving peak discharge values of pre-development state), and the second group presents the minimum GR needed to achieve HHI. In this way, the effect of combining both requirements of HHI can be observed.

Minimum GR in these maps is defined in terms of both the coverage percentage of impervious area and GR type. In the selection of minimum GR, the priority was given to the Extensive Green Roof, meaning if the required result was achieved by 100% coverage by the Extensive Green Roof (EGR100%), this configuration was chosen over any Intensive Green Roof alternative (e.g. IGR30%). The logic behind this selection method was easier installation and lower maintenance requirements of EGR.

4.6.1 Piedmont Hydrologic Soil Group (HSG)

To implement the results into the following compliance maps, it is important to first visualize the distribution of Piedmont's Hydrologic Soil Groups, as different Curve Numbers (CN) were used to represent different native soils in the study.

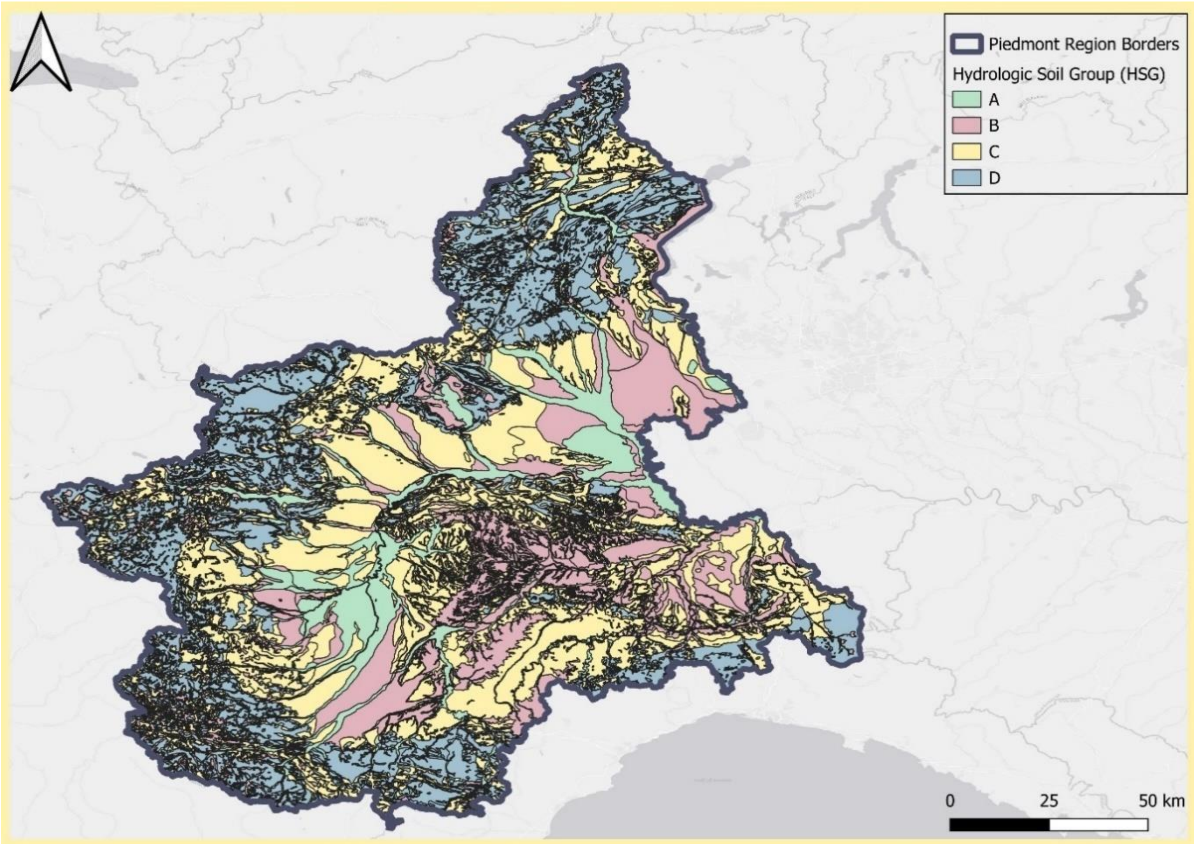

Figure 4.19: Distribution of Hydrologic Soil Groups in Piedmont

4.6.2 Regional Mapping of Hydraulic Invariance

The following six maps illustrate the minimum Green Roof configuration needed for achieving Hydraulic Invariance ($Q_{Peak,LID} \leq Q_{Peak,Pre}$), and the differences in these configurations across different design storm durations.

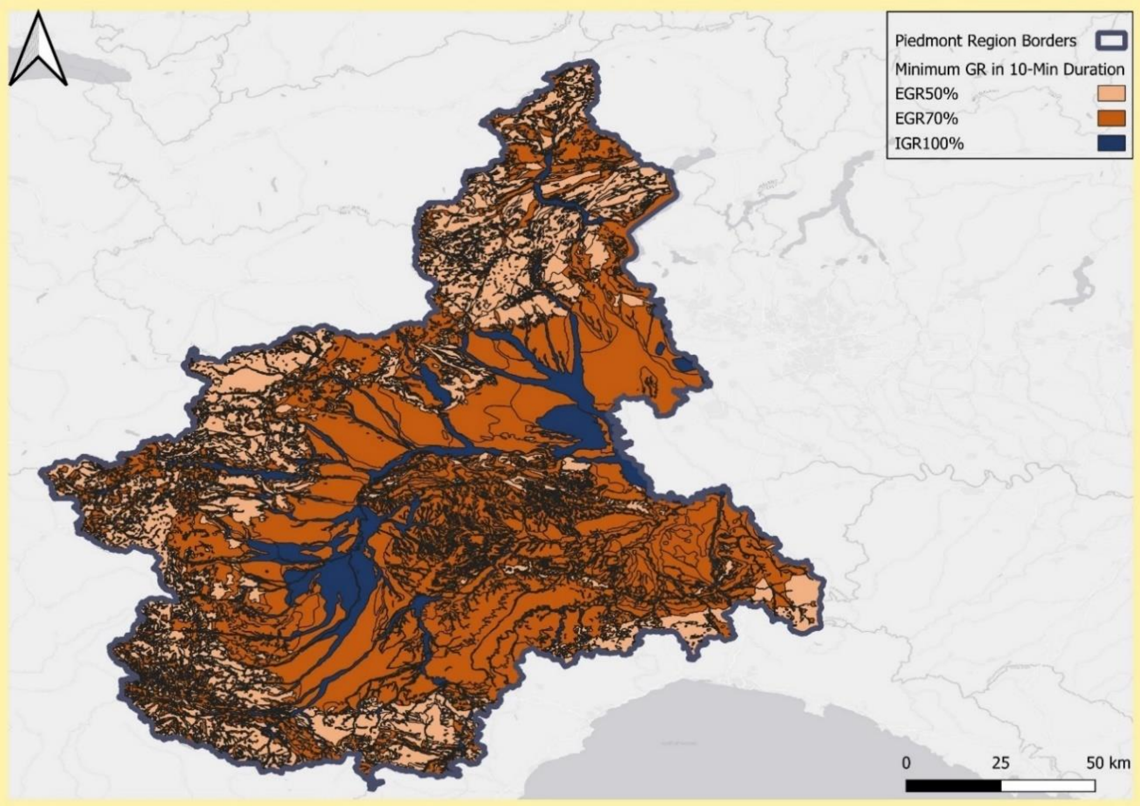

Figure 4.20: Minimum Green Roof to achieve Hydraulic Invariance ($Q_{Peak,LID} \leq Q_{Peak,Pre}$), in 10-minutes duration

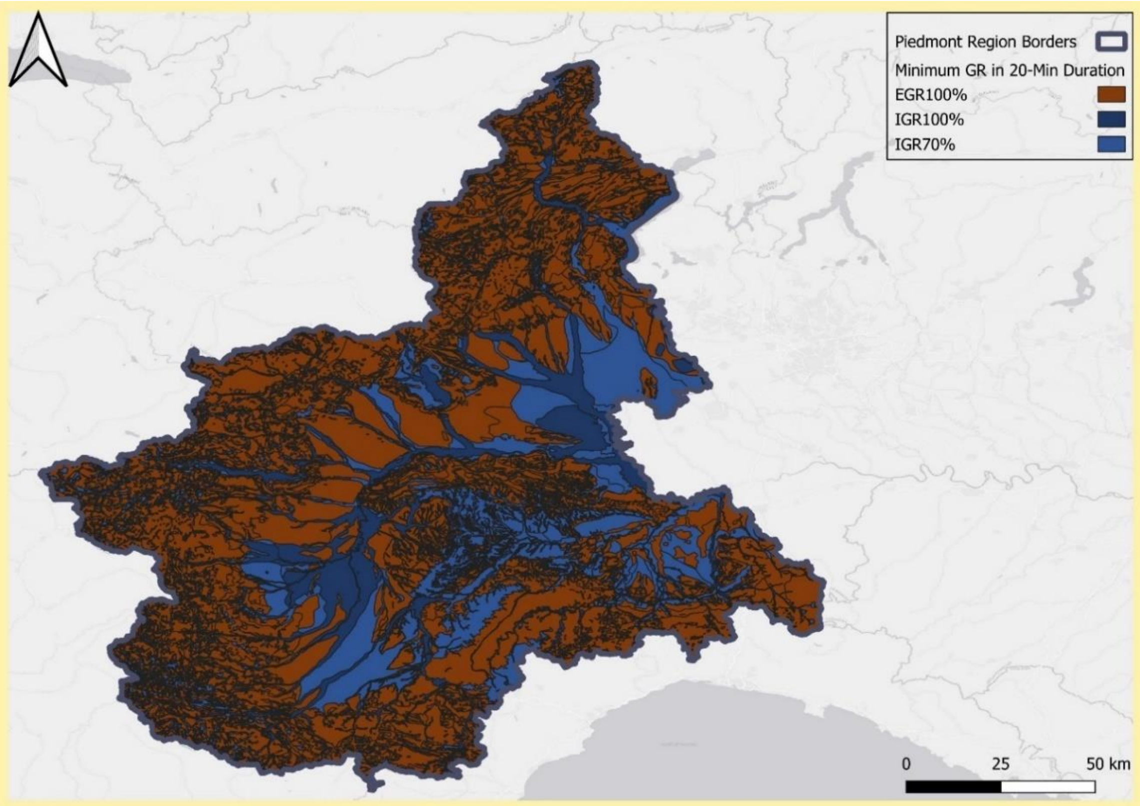

Figure 4.21: Minimum Green Roof to achieve Hydraulic Invariance ($Q_{Peak,LID} \leq Q_{Peak,Pre}$), in 20-minutes duration

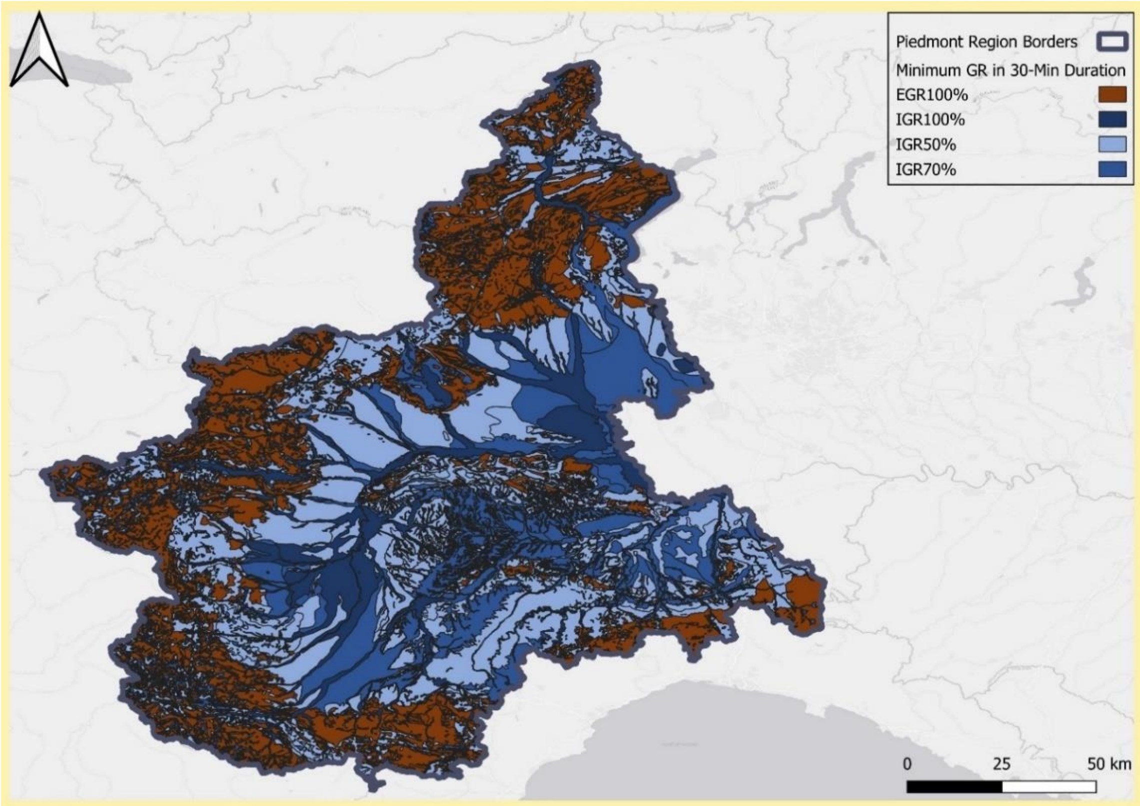

Figure 4.22: Minimum Green Roof to achieve Hydraulic Invariance ($Q_{Peak,LID} \leq Q_{Peak,Pre}$), in 30-minutes duration

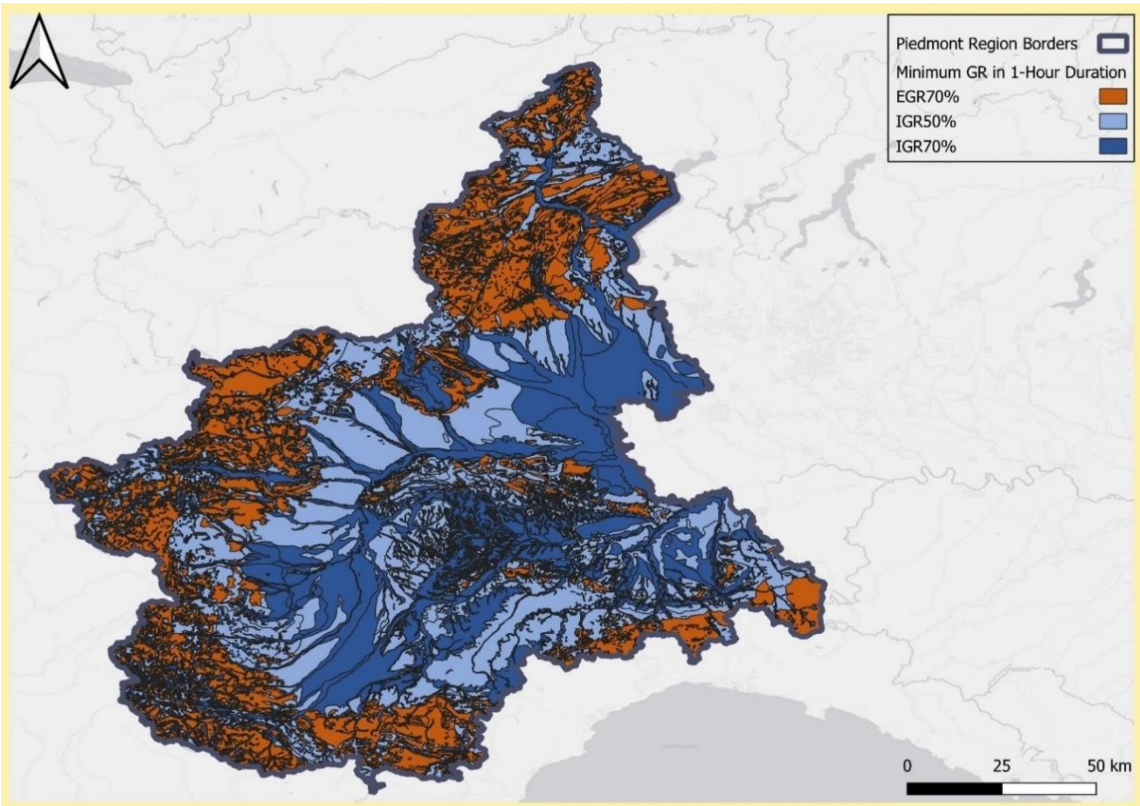

Figure 4.23: Minimum Green Roof to achieve Hydraulic Invariance ($Q_{Peak,LID} \leq Q_{Peak,Pre}$), in 1-hour duration

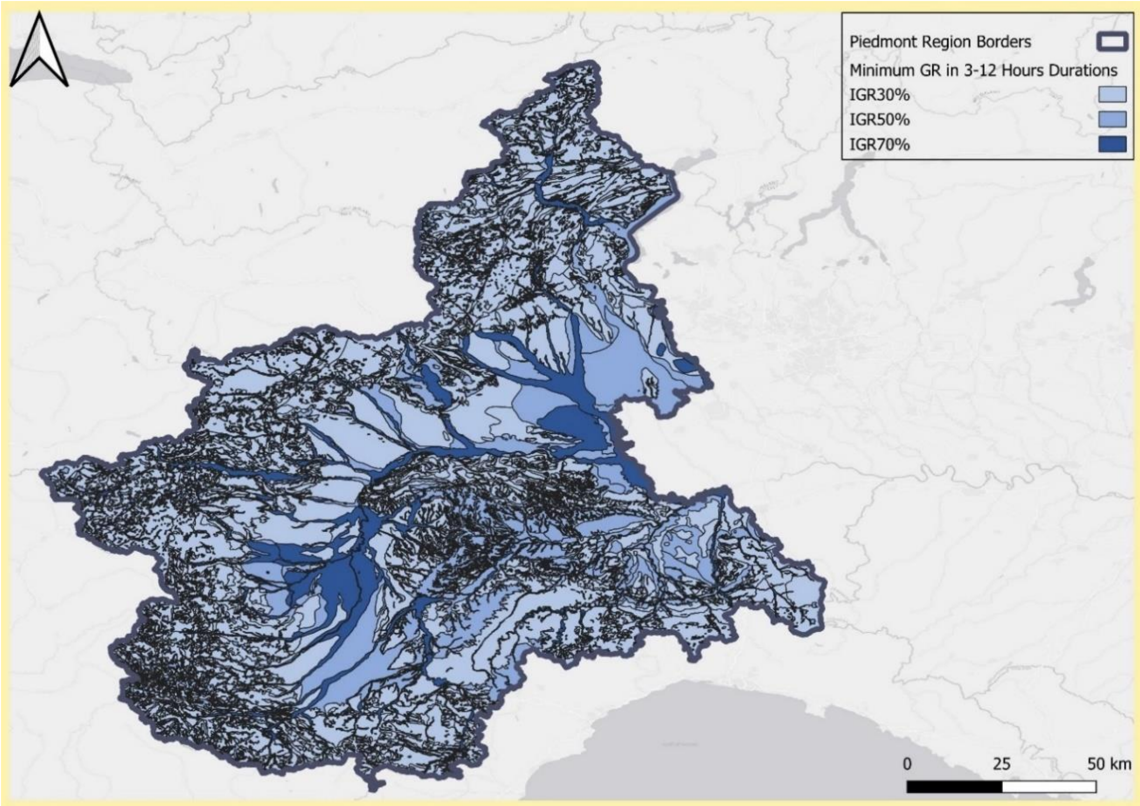

Figure 4.24: Minimum Green Roof to achieve Hydraulic Invariance ($Q_{Peak,LID} \leq Q_{Peak,Pre}$), in 3-12 hour durations

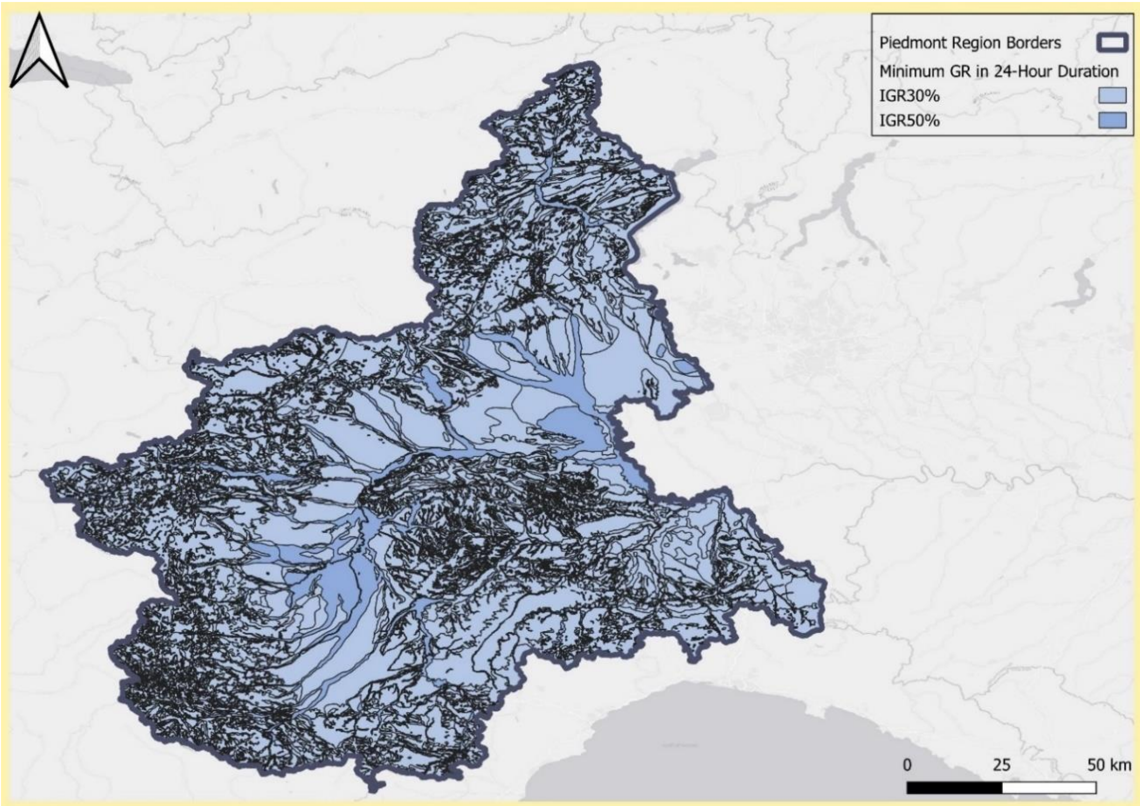

Figure 4.25: Minimum Green Roof to achieve Hydraulic Invariance ($Q_{Peak,LID} \leq Q_{Peak,Pre}$), in 24-hour duration

By following the progression of these maps, the effect of duration and intensity of the rainfall, soil type, and the role of the saturation of the Green Roof's substrate and its timing can be observed.

In 10-minutes duration, which is the shortest (and most intense) duration, the map is dominated by the Extensive Green Roof configurations, as for soil groups B, C, and D, these EGR configurations successfully reduce the peak discharge value to pre-development values. Only in soil group A, the use of a high coverage of IGR (dark blue) is necessary to match the low pre-development value due to the high infiltration of the native soil.

Moving from maps of 20-minutes to 1-hour shows the shrinking EGR effectiveness, and a more dominant role by IGR, as in durations longer than 20-minutes the necessity of its use also includes soil groups B and C, showing a point where the saturation of EGR prevents it from attenuating the peak flow effectively.

During medium to long durations (3-12 hours), the map shows the heaviest configurations of IGR for achieving Hydraulic Invariance, proving that these rainfall durations (and their associated intensity) present the most challenging situation for Green Roofs to reduce Peak Discharge. In the final map (24-hour), the lower intensity of the rainfall event allows lower coverages of IGR to provide enough delay and fulfill the Peak Reduction needed.

4.6.3 Regional Mapping of Hydraulic and Hydrological Invariance (HHI)

This section presents the maps of the minimum Green Roof configurations required for full HHI compliance.

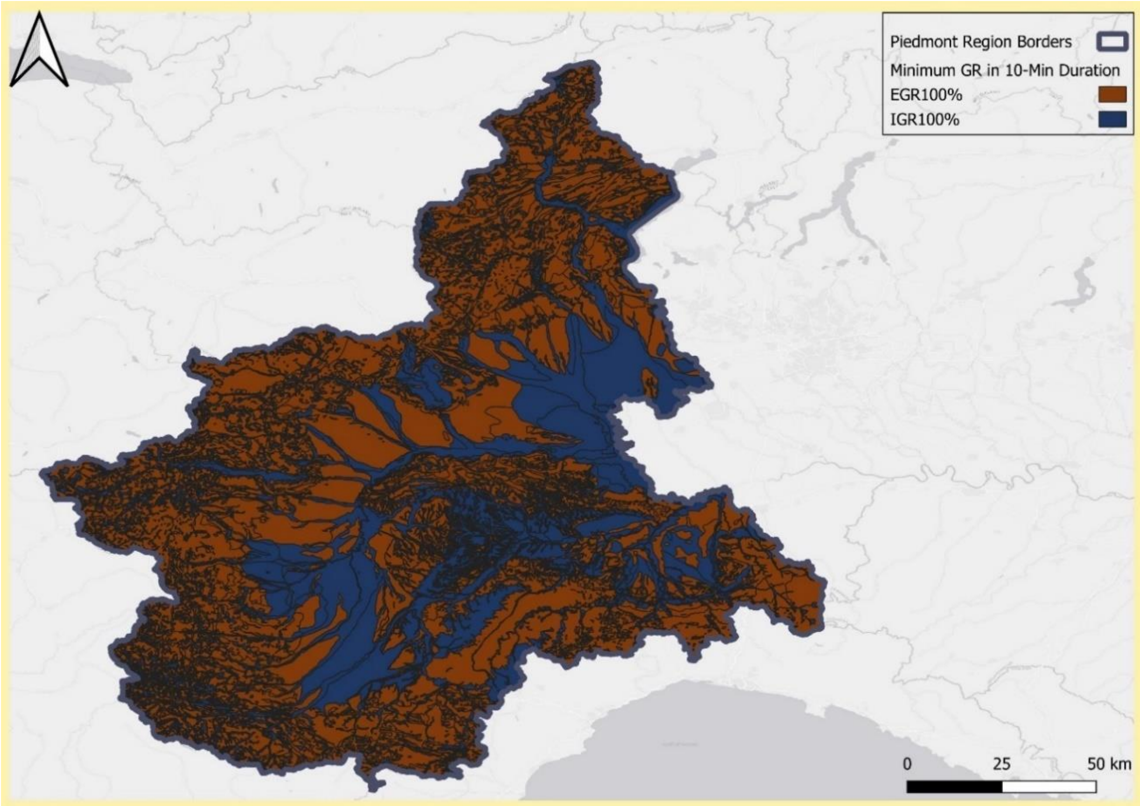

Figure 4.26: Minimum Green Roof to achieve Hydraulic and Hydrological Invariance, in 10-minutes duration

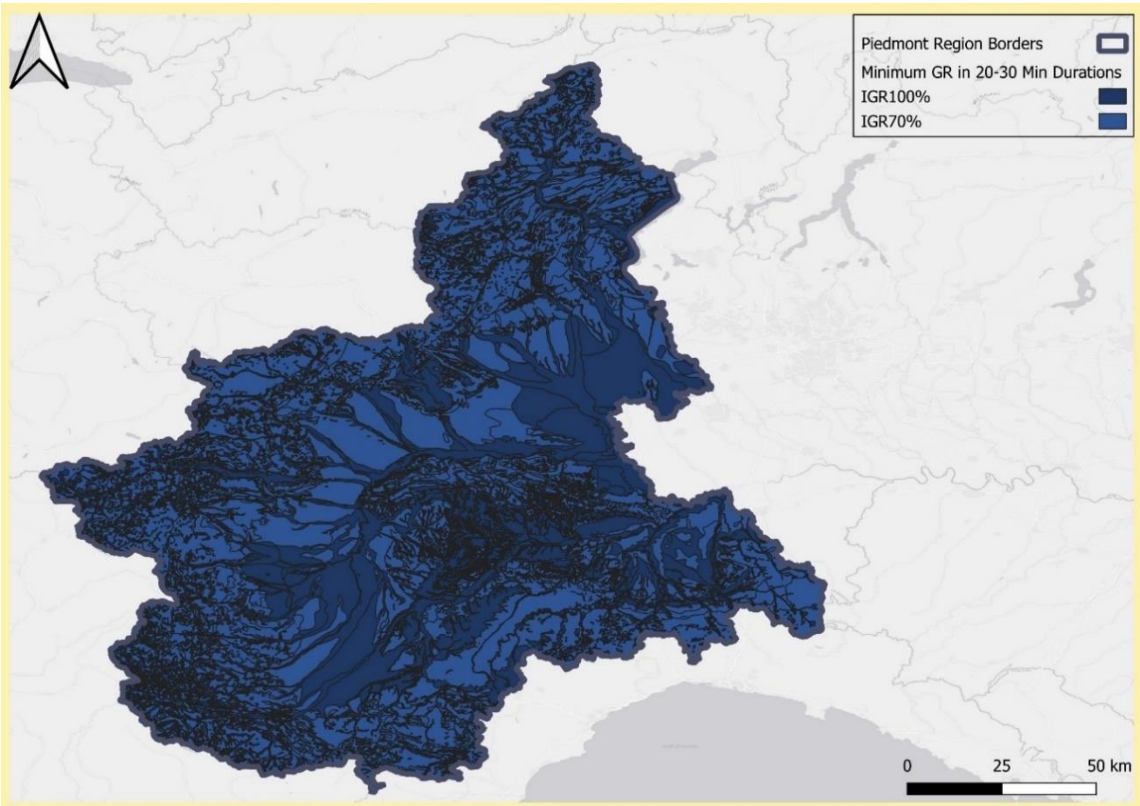

Figure 4.27: Minimum Green Roof to achieve Hydraulic and Hydrological Invariance, in 20-30 minute duration

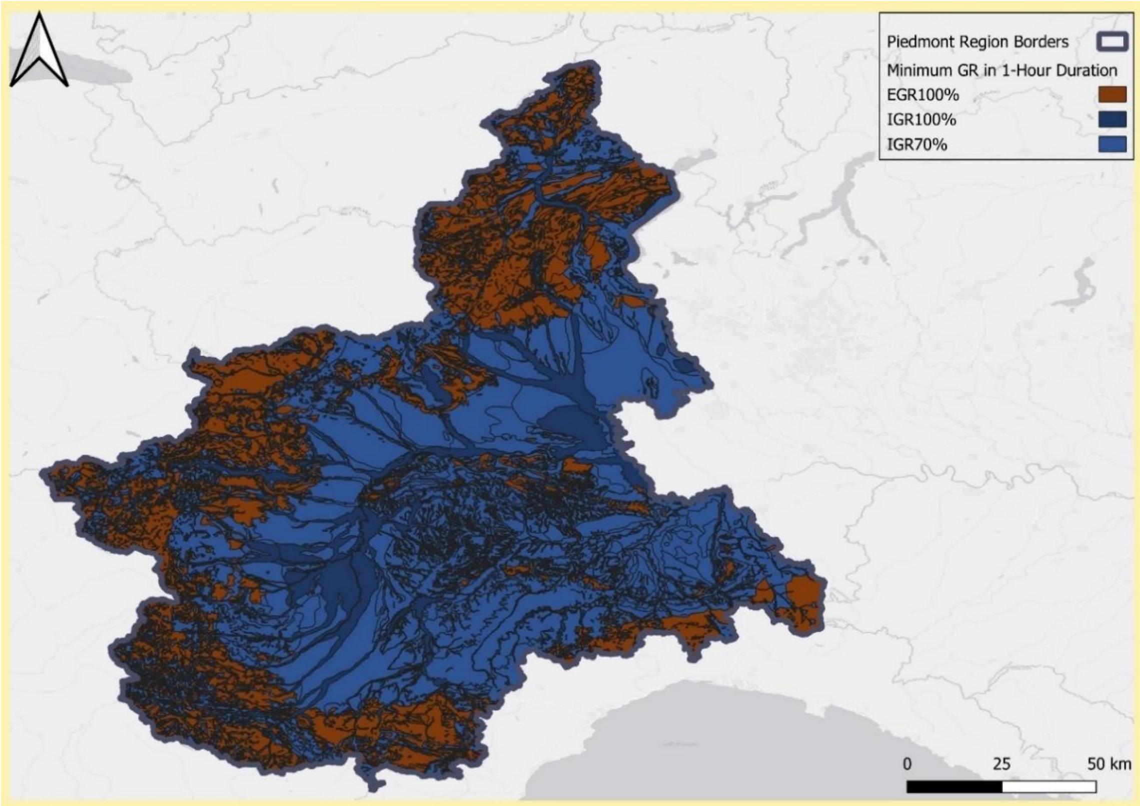

Figure 4.28: Minimum Green Roof to achieve Hydraulic and Hydrological Invariance, in 1-hour duration

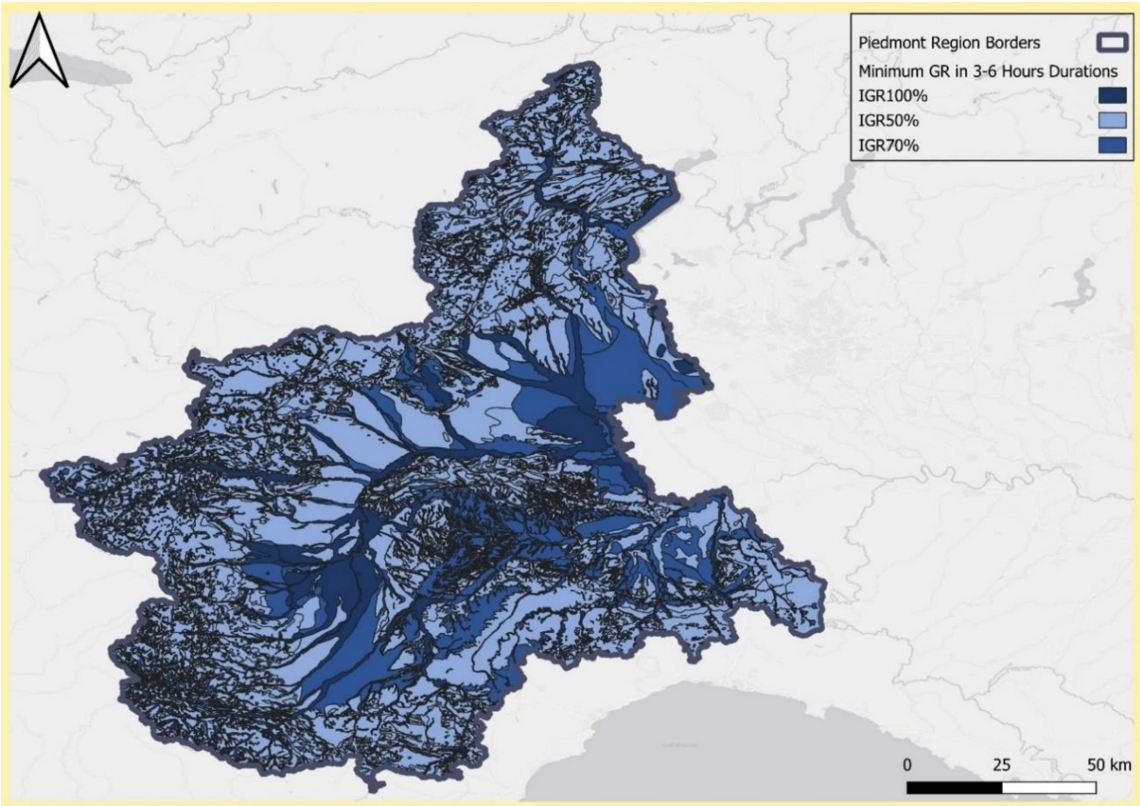

Figure 4.29: Minimum Green Roof to achieve Hydraulic and Hydrological Invariance, in 3-6 hour duration

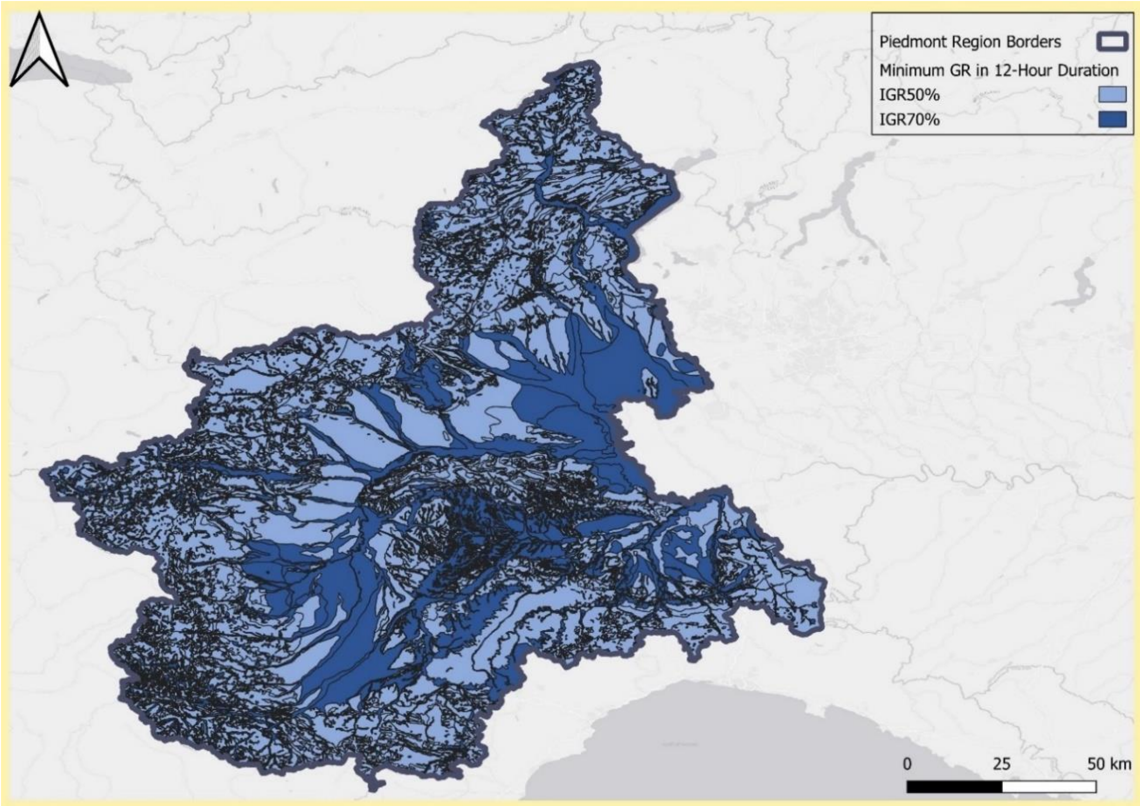

Figure 4.30: Minimum Green Roof to achieve Hydraulic and Hydrological Invariance, in 12-hour duration

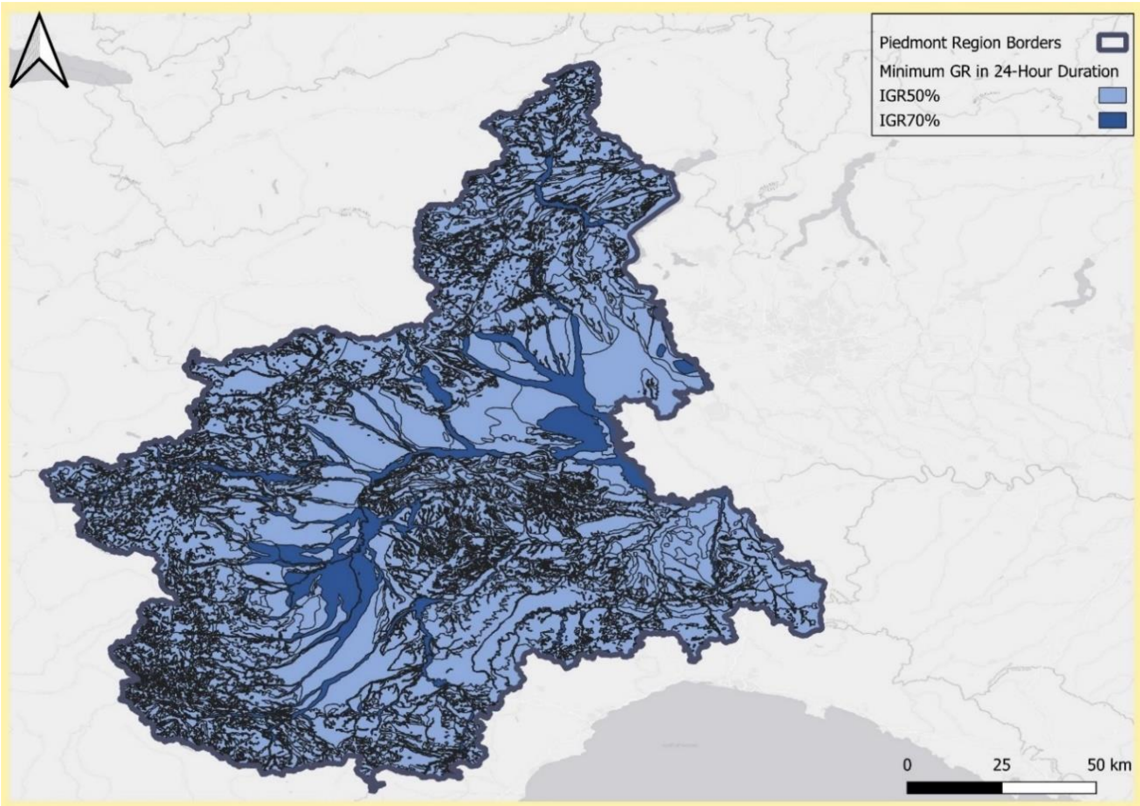

Figure 4.31: Minimum Green Roof to achieve Hydraulic and Hydrological Invariance, in 24-hour duration

As expected, the introduction of Total Runoff Reduction (VR) targets creates much more restrictive results and higher use of IGR.

Even in the shortest duration (10-minutes), the map is visibly including more usage of IGR. Lower coverages of EGR, which were successful in reducing the peak discharge, are unable to satisfy the HHI requirements, and IGR100% and EGR100% have replaced them as minimum Green Roof configurations able of HHI. Before reaching its limited recovery in 1-hour and success with 100% coverage for soil group D, EGR completely disappears from the map for 20-30 minute duration.

The last three maps reveal that, although moving from medium to long durations allows lower coverages of IGR to achieve the targets of HHI, the extent of it is not as pronounced as it was for Hydraulic Invariance (just achieving Peak Reduction needed). According to the results presented on these maps, with the introduction of Volume Reduction requirements of HHI, during rainfall durations of 3 and 6 hours, a considerable area of Piedmont requires the usage of high percentages of IGR (IGR100% and IGR70%). Although in a low-intensity rainfall with 24-hour duration, the necessary IGR coverages subside marginally, still the total cumulative volume of the rainfall requires high storage volumes provided by IGR50% and IGR70%.

These results highlight the fact that for most urban developments, the HHI legislation effectively mandates the use of high coverages of Intensive Green Roof to provide high capacity of storage.

4.6.4 Comparison

To further clarify and synthesize the findings, a direct comparison is made between the 1-hour Hydraulic Invariance and the 1-hour HHI maps, which also helps to better understand the performance of both the Extensive Green Roof and the Intensive Green Roof for the implementation of HHI.

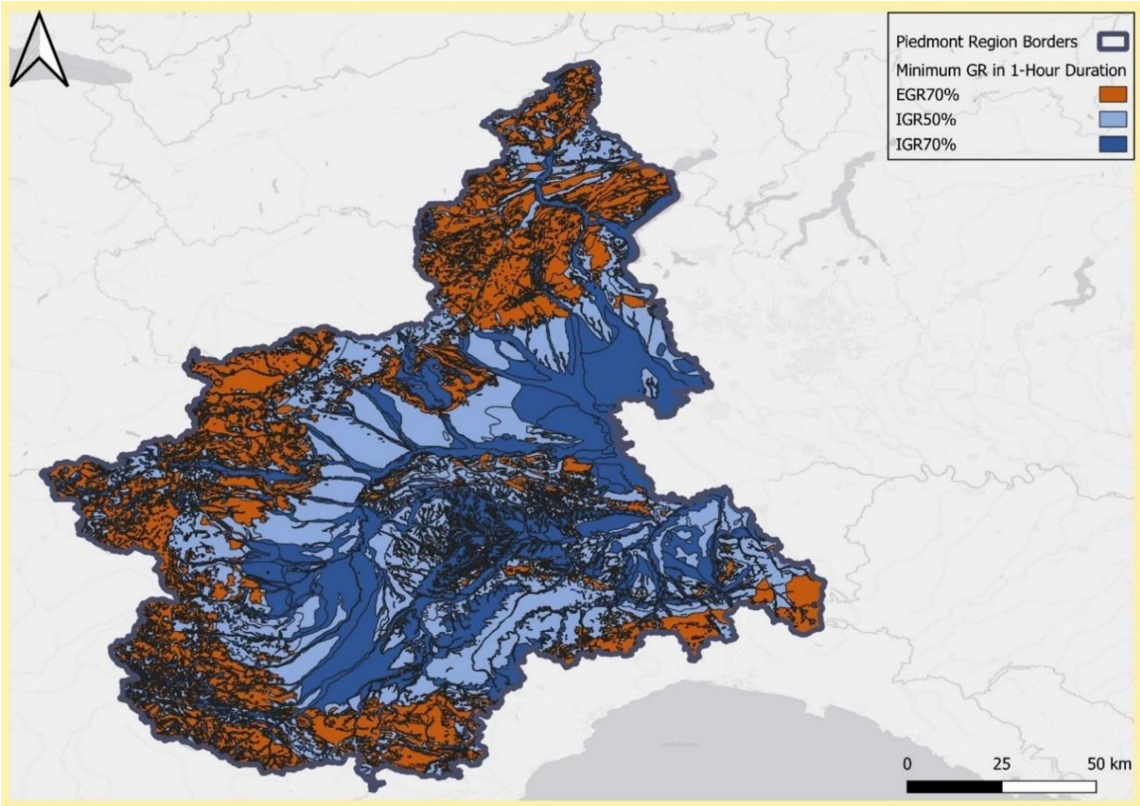

Figure 4.32: Minimum Green Roof to achieve Hydraulic Invariance ($Q_{Peak,LID} \leq Q_{Peak,Pre}$), in 1-hour duration

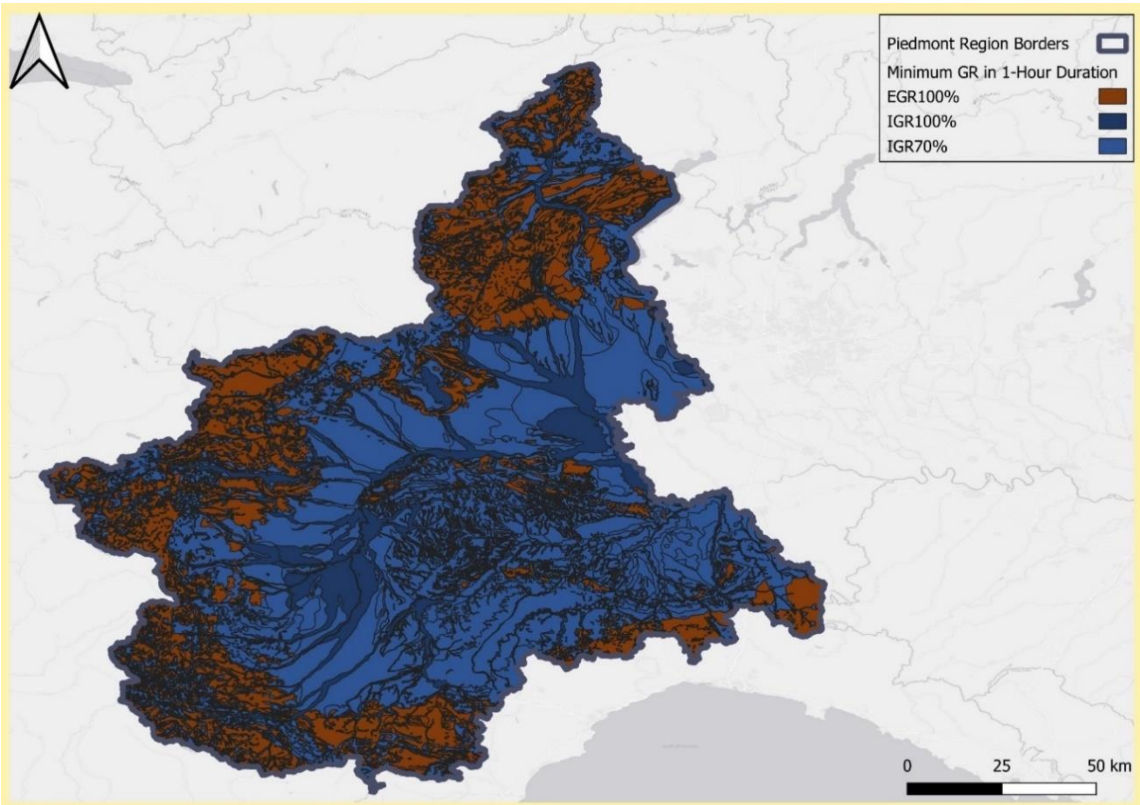

Figure 4.33: Minimum Green Roof to achieve Hydraulic and Hydrological Invariance, in 1-hour duration

By comparing two maps, it is apparent that if the target is set only to achieve lower than or equal peak discharge values compared to the peak discharge of the pre-development state (Hydraulic Invariance), it can be achieved by using lower coverages of Green Roof, which is true for both types. While for HHI compliance, the addition of volumetric requirements (to keep the Total Volume of runoff to values lower than or equal to those of the pre-development state) shifts the minimum Green Roof configurations to higher coverages and ultimately higher capacity systems.

The regional mapping reveals the limitations of the Extensive Green Roof in capturing HHI compliance. Although it is successful in reducing the peak discharge to the required levels during the shorter durations of rainfall, these results are limited to certain soil groups with lower infiltration, and the sufficient results become rarer with longer durations, and failure becomes more common when the volumetric requirements of HHI are also considered.

As for the Intensive Green Roof, the mapping shows that, due to HHI standards, in many instances, a high coverage of IGR is the only option if using Green Roof is being considered as a standalone option. This is especially true for developments with a high-infiltration native soil (e.g. group A), where even in short-duration rainfalls, a high coverage of IGR is needed to achieve HHI.

Chapter 5. Conclusions

5.1 Technical Aspects

The objective of this research was to evaluate the performance of LID Controls for satisfying the Hydraulic and Hydrological Invariance (HHI) requirements. Under multiple rainfall durations, three different types of LID Controls were evaluated, including the Extensive Green Roof (EGR) and Intensive Green Roof (IGR), which were further studied across four distinct Hydrological Soil Groups. The results reveal several critical conclusions regarding the feasibility of LID Control implementation for effective HHI.

5.1.1 The Advantage of Substrate Depth Over Coverage Area

The results show that a high coverage of impervious area by the Extensive Green Roof can achieve positive results during shorter rainfall durations, especially regarding reducing peak runoff; however, it faces a decline in its Peak Reduction performance observed in 3-6 hour durations, and a fundamental lack of storage volume caused by shallow substrate depth resulted in its failure to achieve HHI requirements. In contrast, the Intensive Green Roof acts as an effective LID Control in terms of volume control, with high Volume Reduction potential. The results show that during longer durations of rainfall, 50% coverage of impervious area by IGR proves to be more effective in reducing runoff values compared to 100% coverage by EGR. The substrate depth, then, is the preliminary factor in the effectiveness of LID Controls, including Green Roofs, if other technical parameters remain the same.

5.1.2 Implementation Feasibility and Complementary Measures

While some types and configurations of LID Controls proved to be superior to others in terms of performance in Peak and Volume Reduction, their implementation can be limited by other factors.

The Bioretention Cell proved to be the most effective LID Control in terms of performance, and although it had the least coverage area occupied among the LID Control types, it still needed a considerable surface coverage for achieving HHI, and this coverage area comes at a great cost since it occupies ground-level surface, which can otherwise be used for other land uses.

Permeable Pavement, which can serve as an excellent source control of runoff, has its own limitations, as it needs surfaces with a need for paving on the site for the implementation surface. Usually, in a small urban development, the ground footprint is not big enough for a wide implementation of Permeable Pavement, and in order to achieve HHI, it needs to be integrated with other complementary measures.

The Extensive Green Roof proved to be effective only on some rare occasions, during some short durations of rainfall, and with a poor infiltration of native soil, it managed to achieve HHI by using maximum coverage (100%) of impervious area. This underlines its limitation as a standalone solution for HHI and the need for complementary measures to be used alongside it.

In terms of spatial cost and performance, the Intensive Green Roof emerges as a viable standalone solution. Like EGR, it covers the roof and hence uses the building's footprint as the installation surface. However, in the real world, the Green Roof application faces two significant factors that may limit its use. The first limiting factor for the Green Roof is its weight; when fully saturated, a Green Roof can be significantly heavy, with the IGR being significantly heavier (300-700 kg/sqm) compared to EGR (50-150kg/sqm). This makes the IGR feasible mostly for new urban developments (such as our case study) and less suitable as a retrofitting measure for existing buildings. The second limiting factor is the slope of the roof; According to FLL (2018) guidelines, with an increasing slope of the roof, the water also runs off faster, lowering the efficiency of GR in sloped roofs, which are common in the Piedmont region. These guidelines also recommend avoiding the installation of GR on roofs with a pitch higher than 45° as it can cause several problems.

5.1.3 The Effect of Native Soil on HHI

The results prove that geology, or specifically the native soil of the site, is a primary determinant of success and cost. For example, in a 24-hour rainfall duration with a native soil of Group A, the HHI requirements were so high that an impervious area coverage of 70% by IGR (IGR70%) was necessary for Invariance, while in all other soil groups, HHI was achieved with 50% coverage (IGR50%). The results prove that, with an increase in native soil infiltration capacity, the cost of interventions also increases, as there will be a need for wider use of LID Controls.

5.2 Planning Aspects

This study provides insights into the application of Hydraulic and Hydrological Invariance requirements in the Piedmont's regulatory framework, particularly under Regional Council Resolution (D.G.R.) 8-905/2025 and Regional Regulation 1/R/2006.

5.2.1 Design Storm Selection

The results prove that using the time of concentration (T_C) as a basis for design storm selection can be effective for peak discharge control, as it predicts the most instantaneous flow rates. However, this study proves the fact that controlling peak discharge and total volume represent two distinctive objectives that can require different critical durations. This is important since T_C in a small catchment is usually short, and the selected design storm based on it will also be short. Guidelines should avoid T_C, and mandate a dual objective analysis across multiple durations of rainfalls to determine the critical duration that produces the most restrictive measures for both peak discharge and total volume of runoff.

5.2.2 HSG and HHI Compliance

The Hydrologic Soil Group (HSG) distribution across the Piedmont creates significant variability in HHI achievability. The results show that the HHI targets are defined based on the infiltration potential of the natural soil of each area, and these targets require different LID Control implementations. Based on this, regional planning should avoid promoting a certain type of technology and establish a performance-based approach, for example, if using Green Roofs is not possible, alternative solutions such as Bioretention Cells, Detention Tanks, or hybrid systems should be permitted, provided that it can be proved they can achieve HHI.

5.2.3 New Tools

The study's HHI Maps (Figures26-31) show the possibility of developing regional planning tools that can support decision making process.

These tools can potentially provide:

- Minimum LID Control requirements for each specific site based on the HSG, which can be checked before going through the process of detailed design

- Compliance verification through standard performance references
- Identification of areas where HHI application can limit the densification of new developments
- Support for municipalities that lack sophisticated hydraulic modelling measures

The region can integrate these tools into existing digital platforms, such as Sistema Informativo Territoriale Regionale, to support both municipalities and designers with maps that can provide data on the HHI application.

5.2.4 Recommendations on Policy Updates

Some updates can be done to incorporate the technical and economic realities of HHI implementation into the policy while maintaining the ecological essence of HHI policy. These suggestions are based on the conclusions discussed above.

- Mandate a multi-duration analysis of rainfalls for finding the critical duration and selection of the design storm
- Develop standard and simplified compliance metrics for developments with similar characteristics and soil conditions
- Develop exemption policies for developments with feasibility constraints, through alternative pathways

5.3 Concluding Remarks

This study concludes that to achieve full compliance with HHI across Piedmont, a heavy application of Intensive Green Roof is needed. Under current regulations, the use of these high-weight, deep substrate systems is mandatory if used as standalone solutions. The weaker results from Extensive Green Roofs show the necessity of pairing them with additional complementary measures, such as storage volumes provided by detention tanks. A detailed cost-benefit analysis comparing these two solutions can be helpful to guide decisions in the future. Future research can potentially also explore smart solutions that can use the limited storage volumes more efficiently and allow for the time-dependent hydrological processes, such as infiltration, to take place.

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