

Green Roofs and Compact Infiltration Systems in Malta: A Modelled Assessment of Runoff and Peak-Flow Reduction for Urban Flash Flood Mitigation

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Abstract

Flash flooding is a type of hazard characterised by intense rainfall over a relatively short period (Abegaz et al., 2024), significant economic and health harms (Alipour et al., 2020), and a pattern of accelerating increase in terms of frequency and intensity due to climate change. Additionally, urbanised areas are particularly vulnerable to hazards associated with these extreme weather events, due to their traits of impermeability that increase runoff generation. Within Malta, flood risks have also been intensified by the inconsistent implementation of adaptation measures, particularly the integration of rainwater cisterns into buildings. Although rainwater cisterns have long been required by law and form part of Malta's traditional approach to rainwater management, periods of rapid development have seen these measures overlooked or inadequately implemented. Consequently, rainfall that could otherwise be stored or managed on site is often discharged directly onto streets, contributing to surface runoff and urban flooding.

This study describes and compares the potential benefits of individual and combined green stormwater infrastructure (GSI) measures through their effectiveness in reducing flood impacts, especially flash flooding, in terms of reductions in total runoff contribution and peak flow. The individual and combined impacts of both green roof and compact infiltration system (CIS) GSI are explored. Green roof GSI refers to rooftops that utilise green space, incorporating vegetation and soil, to manage overflowing stormwater through absorption and retention. Alternatively, CISs are infiltration systems developed locally within Malta through a research project named GEO-INF conducted by Ing Marco Cremona, and are characterised by their compact size, low costs, and low maintenance (*Green Stormwater Infrastructure Guidance Manual*, 2022). These potential benefits in mitigation effectiveness are explored within an 8028 m² study area within Birkirkara, Malta; a densely populated and heavily urbanised area known for flooding downstream.

These GSI types are explored through modelled simulations in Stella Architect, based on Maltese weather data and GSI data from current GSI projects, with the express purpose of testing mitigation effectiveness across a variety of storms that emphasise current averages, increasing intensities, and increasing temporal scales. In total, four scenarios were modelled and tested for effectiveness, including no GSI implementation, green roof, CIS, and integrated green roof and CIS implementation.

The results of this study show a substantial runoff contribution reduction across all scenarios featuring GSI, with the integrated green roof and CIS scenario mitigating approximately 100% of runoff contributions and peak flow rates across all storm scenarios. The CIS scenario showed complete mitigation in scenarios where its capacity was reached; however, in other scenarios, increased runoff and especially peak flow rates occurred. Green roofs showed greater resilience across all storms and held an 88% runoff reduction percentage against storm seven, as opposed to the 37% runoff reduction percentage exhibited by the CIS scenario in the same storm event. Finally, the GSI scenarios were analysed under varying roof area and CIS tank size configurations to find further optimisation opportunities, with significant tank size reductions being found to be effective for the combined green roof and CIS scenario.

This study holds implications for the tradeoffs present across different GSI configurations, through the comparisons identified and the overall evidence for the effectiveness of alternatives and complements to conventional stormwater drainage infrastructure, including rainwater cisterns. Overall, this study addresses knowledge gaps relating to key GSI types that will be necessary to reduce the increasing impacts of flash flooding events, as they grow in intensity and frequency, due to climate change.

Keywords: flash flooding; green stormwater infrastructure; compact infiltration system; green roof; hydraulic modelling; climate change; Malta.

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1. Introduction

There is a pattern of intensification in the severity and frequency of extreme weather events that is predicted by many climate scientists to continue and escalate. One such extreme weather event particularly susceptible to intensification from climate change impacts is flash flooding, often characterised by rapid runoff generation and short warning times. This intensification occurs because increasing temperatures intensify key flood drivers, including rising sea levels, increasing precipitation, and more severe storms (Azhar et al., 2025). Additionally, higher atmospheric temperatures elevate moisture-holding capacity, resulting in more intense and prolonged precipitation that overwhelms drainage infrastructure, thus triggering flash flooding (Azhar et al., 2025). Consequently, this continual intensification of climate change impacts particularly amplifies and elevates the impacts and likelihood of flash flooding hazards.

Due to these current and increasing vulnerabilities, many forms of adaptation measures and infrastructural plans have been proposed to reduce the risks present within these urban areas. These measures can be primarily divided between grey infrastructural methods and green stormwater infrastructure (GSI). Grey infrastructure can be defined as human-made engineering solutions, such as dams, levees, and floodwalls, that, while serving as helpful protective mechanisms, also come with limitations associated with their expenses, implementation timescales, and potential failure (Abegaz et al., 2024). As defined by the Maltese Ministry for Public Works and Planning, GSI can be defined as infrastructure designed to mimic nature and capture rainwater where it falls, and includes rainwater harvesting systems, green roofs, trees, rain gardens, infiltration systems, and pervious pavements (*Green Stormwater Infrastructure Guidance Manual*, 2022). While these methods come with their own drawbacks, some studies have found proven efficacy in managing flood risks (Abegaz et al., 2024). Consequently, this study is specifically focused on GSI adaptation infrastructure.

The purpose of this project is to compare and evaluate the individual and combined effectiveness of two GSI methods, green roofs and compact infiltration systems (CIS), in terms of reducing stormwater runoff volume and peak discharge, within the low-lying urban area of Birkirkara, Malta. These individual and combined adaptation measures were modeled (via Stella Architect) to assess effectiveness in the reduction of stormwater generation, quantified as percent reduction in event runoff volume and peak flow relative to the baseline scenario. Through the modeled findings, local communities and urban planners can be supplied with greater knowledge of the assessed mitigation effectiveness of differing GSI types and combinations. In turn, these findings of mitigation effectiveness help to inform important decisions regarding GSI tradeoffs between flood resilience and costs/efforts of implementation and maintenance.

Overall, this project describes and compares the potential benefits of green infrastructure systems if implemented and executed within Maltese urban zones. The urban area around St Aloysius College was chosen because Birkirkara is a heavily urbanised area known for flooding downstream in Valley Road and an operational CIS pilot. In addition to this present risk, climate change drivers are slated to increase flash flood events in both terms of frequency and intensity. This project analyses, compares, and evaluates urban planning measures of adaptation that will be necessary as impacts of climate change

become more apparent and severe. Through its evaluations and comparisons, this project produces site-specific evidence on the performance of green roofs and CIS individually and in combination. In addition to the project's contributions to evidence of green infrastructure effectiveness within the study area, this project also holds relevant application to other areas within Malta and abroad, especially those holding similar climatic and geological characteristics.

2. Background

While a wide variety of scholarly literature about nature-based solutions and their studied efficiencies and applications has informed this proposed study, it is important to first emphasise the scholarly sources that influenced the exact definition of the problem this study aims to alleviate. One literature review on the history, trends, and causes of flooding defined flash flooding as a type of pluvial flood that “can occur within minutes to hours after the triggering event and is particularly dangerous due to its sudden occurrence” (Abegaz et al., 2024). As shown above, the true concern with flash flooding is the lack of predictability and warning at the time of occurrence. This hazard also presents significant vulnerabilities to populations residing in urbanised zones, which are expanding rapidly in area and population (Rentschler et al., 2023). These flood events contribute to both devastating economic and health harms through property damages, fatalities, and injury (Alipour et al., 2020). Finally, “climate change is driving up the probability of extreme natural shocks... [and] determined patterns of urbanisation and spatial development are key factors in the exposure and vulnerability of people to climate shocks” (Rentschler et al., 2023). Through the combination of these trends, it is clear that flash flooding events pose a significantly increasing risk to the many growing urban areas and must be addressed through appropriate infrastructure development and adaptation measures.

2.1 The Maltese Context

The problem this study assessed is not only strictly defined by the hazard of flash flooding but is also characterised by the unique context of Malta. This problem is influenced by the climate, physical characteristics of the islands, and recent history of intensive development. Malta is an island nation in the Mediterranean Sea with an area of 316 square kilometers (km²), which features a climate typical of the Mediterranean, with hot, dry summers, warm and sporadically wet autumns characterised by isolated showers, cool winters with moderate rainfall, and warm and dry springs with occasional showers (Galea, 2009). Malta's geology is primarily defined by coralline limestone formations, blue clay, and green sand (Pedley et al., 1976). These geological characteristics of high permeability and dissolution create high infiltration and flow rates for surface water toward groundwater reservoirs, making Malta a classic example of a karst aquifer system. Additionally, Malta received approximately 550 mm of rainfall per year from 1940 to 2024, with considerable annual fluctuations. Despite these averages, there is a trend of decreasing annual rainfall that was found to be present for 12 out of the last 16 years (*Water Scarcity and Drought Conditions in the Maltese Islands*, 2025). This is largely due to longer drought periods.

Despite this trend of decreasing annual precipitation averages, Malta still consistently experiences flash floods (*National Climate Change Adaptation Strategy*,

2010). Additionally, these trends are predicted to be accelerated through increased climate change impacts over future decades. These combined trends of increased drought periods and consistent flood hazard risk represent a complicated case that requires careful and detailed water management.

Malta's unique water management context is one not only defined by increased extremes in weather but is also characterised by the recent history of urban development in the pursuit of economic growth that has taken place at an accelerated pace since the second half of the 20th century. Specifically, this period was characterised by a high population increase, rapid economic growth, and an increase in the general standard of living of the population, thus causing a large increase in water demand (Sapiano et al., 2008). Consequently, Malta and Gozo experienced exceptional urban and infrastructural growth at a rapid rate that very much outpaced policy frameworks and direction for planning relating to urban growth (Pace, 2025). This is evidenced by the fact that until around 1988, development was largely unrestricted (Pace, 2025). Additionally, despite some legislative reforms and efforts of the past 30 years, Malta still faces challenges to urban planning, including the negative influence of construction lobbies, political patronage, and land corruption (Pace, 2025). These trends have led Malta to feature many unplanned, dense urban zones that hold inconsistent management practices.

While this rapid development has contributed to increased GDP and the establishment of Malta as a developed country, the lack of planning has resulted in fragmented land areas and increases in urban spaces. Large areas of urban space translate to large tracts of territory being sealed, leading to reduced capacity for water retention and accentuation of flooding (*National Climate Change Adaptation Strategy*, 2010). This water retention decrease is caused by the way developed, tarmac, and impermeable surfaces decrease the amount of rainwater infiltration, thus causing increased amounts of surface runoff (Galea, 2009). Essentially, urban areas hold greater risks of flash flooding hazards, through the impermeability commonly associated with their building materials. Overall, this combination of unprecedented rapid urban development, limited urban planning, and permeability characteristics has led to exceptional and increasing risk of flash flooding within Malta's expanding urban areas.

2.2 Water Management in Malta

First, it is important to look at how water has traditionally been managed on the Islands, before rapid development complicated management practices. Due to the island's limited freshwater resources, water supply has primarily relied on a combination of groundwater abstraction and rainwater harvesting, such as rainwater cisterns in individual Maltese homes and buildings. However, in recent decades, in accordance with rapid development, the country has relied to a greater extent on groundwater abstraction and increasingly on seawater desalination and less on rainwater harvesting and use. Malta's reliance on groundwater abstraction combined with unsustainable water consumption results in abstraction exceeding the annual recharge, hence leading to groundwater quantity and quality degradation (*A Strategic Framework for Green Stormwater Infrastructure across the Maltese Islands*, 2023). Overall, these trends in water use and collection not only intensify the likelihood of flash flooding (through the decreased emphasis on rainwater harvesting) but also harm the groundwater supply through both unsustainable over-

abstraction and decreased groundwater recharge rates caused by the interference of impermeable urban materials toward precipitation's eventual flow towards groundwater. Consequently, water management plans must emphasise a holistic analysis of the water system, incorporating elements of water supply and demand, urbanisation trends and other anthropogenic drivers, as well as current and changing weather patterns.

The 3rd River Basin Management Plan serves as a primary water management authority that provides procedures to ensure and define status assessment and also proposes a complex and sprawling programme of measures to achieve “good” ecological and chemical status within Malta’s water bodies. One such programme of measures includes supporting schemes for the promotion of green urban infrastructure. Specifically, this programme aims to enable households and local authorities to invest in greening initiatives in urban areas such as green roofs, green walls, and green spaces (*3rd River Basin Management Plan*, 2024). The plan further emphasises the importance of green infrastructure from a water management perspective by stating how it serves to optimise the management of rainwater runoff, reduce flood risk, and increase the recharge to groundwater (*3rd River Basin Management Plan*, 2024). While there are many proposed measures within the management plan, these green infrastructure measures are prioritised relatively highly among the total, ranking 18th out of 35 proposed measures. This river basin management plan shows a clear recognition of the importance and potential impact that green infrastructures serve for managing flood risk and water supply within Malta. Even more importantly, this plan shows that the Government of Malta is in support of these measures, thus making them hold a greater chance of success in implementation. The plan also highlights the importance of using the results from the GSI guidance manual, a comprehensive document that defines and assesses many differing GSI types, to identify the water management potential of GSIs within distinct areas, in ensuring water quality and quantity status, while also mitigating potential hazards.

2.3 Birkirkara

As the aim of this study is to assess the success of two distinct GSI types within the low-lying urban zone of Birkirkara, this zone must be properly defined and contextualised. Birkirkara is located in the central part of Malta and is a large settlement with a primary town centre surrounded by peripheral residential schemes (Borg, 2017). Additionally, Birkirkara is currently one of the largest localities within Malta, holding a population of approximately 29,482 residents, as of 2025 (*World Population Day: 11 July 2025*, 2025). Associated with this change in population is the rapid shift in land use and urban density that took place during the 2nd half of the 20th century, which was marked by construction that lacked proper planning and the use of any studies regarding demographic, physical, and environmental impacts (Borg, 2017). Indeed, as identified in the referenced study regarding changing urbanisation conducted by Rainer Borg, annual building/housing developments only began to slow once absolute physical limitations of space within the locality were reached (Borg, 2017). Consequently, Birkirkara is marked by crowded and poorly planned urban housing and design, thus making it susceptible to flash flooding hazards.

As a result of these trends, Birkirkara serves as a microcosm of the issues Malta currently faces in regard to the management of water and associated flooding hazards.

These flood risks have traditionally been mitigated with rainwater harvesting systems such as rainwater cisterns, which, as stated in the GSI manual, are required in the construction of buildings, as of 2022 (*Green Stormwater Infrastructure Guidance Manual*, 2022). Specifically, rainwater cisterns hold volume requirements equivalent to 45% of the total rooftop area (*Technical Document F Part 1: Dwellings Minimum Energy Performance and Building Envelope Requirements*, 2023). However, rainwater cisterns are not consistently being built in apartment buildings and terraces (*Green Stormwater Infrastructure Guidance Manual*, 2022). This is likely due to a local lack of enforcement and local avoidance of high construction/maintenance costs. This ongoing lack of consistent infrastructure implementation within Malta has intensified the high flash flooding risk already present within the densely packed, low-lying, urban area. However, alternative forms of GSI could serve an important role in minimising flood risks within this area, while also creating synergies for avenues relating to water management in both terms of supply and hazards.

2.4 Infrastructural Adaptation Measures

There are a variety of proposed measures to mitigate the risks of flash flooding that mainly fall between grey (built) and green (ecosystem-based) infrastructure. However, green infrastructure is gaining increased traction due to its lower costs relating to introduction and maintenance, provision of ecosystem services, and local community development, among others (Onuma & Tsuge, 2018). Furthermore, green infrastructure has shown particular promise for the management of urban flooding risk, with one study finding that integrated green infrastructure configuration held substantial reduction percentages, especially for total runoff reduction and peak flow reduction (Liu et al., 2014). However, despite this general consensus of the effective nature of green infrastructure, there is a wide variety of types and forms within the umbrella term.

Within Malta, there are many examples that fall under green infrastructure, locally termed Green Stormwater Infrastructure (GSI). Some of these examples of GSI, which the Ministry of Public Works promotes and provides guidance for, include RWH systems, green roofs, soakaways (infiltration systems), filter strips, pervious pavements, and compact infiltration systems (CIS) (*Green Stormwater Infrastructure Guidance Manual*, 2022). Of specific interest to this study are green roofs and CIS. These GSI types have been studied in their individual general efficiencies (to varying degrees), but still present significant knowledge gaps in their performance, specifically in understanding their total runoff reduction and peak flow reduction, especially within a Maltese context. Additionally, there are knowledge gaps in the understanding of further optimisation of these individual GSI types. These knowledge gaps not only exist within their individual performances but also within the potential combined performance of these adaptation measures.

Green roofs refer to rooftops that utilise green space, incorporating vegetation and soil, to manage overflowing stormwater through absorption and retention, while also providing other environmental and energy benefits. Green roofs have been found to be eminently effective in the Maltese climate, where they are intended primarily for interception storage within the vegetation and also the substrate (*Green Stormwater Infrastructure Guidance Manual*, 2022). Green rooftop efficiencies and benefit synergies are continually being discovered and advanced, with recent findings including systems

where surplus runoff can be re-used on the same green roof and layouts that can accommodate green roofs for installation of photovoltaic (PV) modules (*Green Stormwater Infrastructure Guidance Manual*, 2022). However, green roofs do hold limitations in their effectiveness, such as the physical impacts of roof pitching (flatter roofs produce greater efficiencies), accessibility and supervision concerns (depending on the green roof type), and costs/retrofitting concerns to ensure proper construction of all vital elements, such as a robust waterproofing layer (*Green Stormwater Infrastructure Guidance Manual*, 2022). Despite these limitations and costs, their efficiency at controlling flooding has been widely studied within a variety of contexts, with one study based on a densely populated urban area within China finding “that GRS [green roof systems] can retain about 41-75% of precipitation in a 2-hour timescale” (Liu et al., 2020). While green roofs do feature specific tradeoffs and limitations associated with their implementation (especially for retrofitting), their studied efficiencies towards runoff mitigation, secondary benefits, and continued advancement are undeniable; thus, making them a particularly powerful GSI, especially given the Maltese context.

While there are a variety of ongoing green roof infrastructure projects within the Maltese context, the experimental green roof project in Rabat serves as an exceptional project in terms of both mitigation effectiveness and data collection. This project has been conducted by the Energy and Water Agency at the Ghajn Water Conservation Centre since 2023 and has been continually collecting data regarding their findings in the 3000-plant rooftop garden’s ability to mitigate rainfall. This project specifically functions by recording data from incoming rainfall with a rain gauge on top of the roof (in millimeters) and then recording overflow values (in litres) through four pipes through which the water is transported once the total capacity/retention of the green roof is reached and surface runoff begins to accumulate. The green roof project has been continually monitored, maintained, and at times repaired; thus, leading to the production of valuable and reliable data, especially throughout the period of late 2024 to mid-2025.

CISs are infiltration systems developed locally within Malta through a research project named GEO-INF, conducted by Ing Marco Cremona, and are characterised by their compact size, low costs, and low maintenance (*Green Stormwater Infrastructure Guidance Manual*, 2022). A CIS functions by draining runoff rainwater from roofs down through pipes, passing through storage tanks, and then finally passing through a gravel filter into a borehole that has been drilled halfway through the unsaturated zone (*Green Stormwater Infrastructure Guidance Manual*, 2022). Now of specific interest regarding this GSI is the fact that the water dissipates into the rock through the sides of the borehole once it has passed the gravel filter; dissipation rates are primarily influenced by the permeability of the rock layers, but also by the depth and diameter of the borehole (*Green Stormwater Infrastructure Guidance Manual*, 2022). Consequently, this GSI not only regains its storage capacity over time but also helps regenerate groundwater supply through dissipation of (filtered) water to underground reservoirs. However, since groundwater is being impacted, it must be ensured that incoming rainwater is not carrying pollutants that could harm the underground reservoir. Some ways identified by the GSI manual to safeguard against this risk include limiting CIS to rooftops, ensuring borehole depth does not exceed 50% of the depth of the aquifer, guaranteeing inaccessibility of rooftops to pets or storage of materials that leach contaminants, and requiring proper risk assessments before installation (*Green Stormwater Infrastructure Guidance Manual*, 2022). Despite the noted limitations and

insights from the GEO-INF project, CISs still represent a fairly new and relatively less studied GSI, thus presenting significant knowledge gaps in terms of large-scale implementation, long-term impacts, and site-specific optimisation.

While CIS is relatively new and specific to Malta, the process of infiltration and impacts of infiltration systems have been studied widely. Infiltration systems have been shown to have an effective impact in reducing water depths and delaying peak flood times from high precipitation events, both through the diversion and retention of stormwater (Tügel et al., 2020). Despite these efficiencies, the geography of the land where the infiltration system exists has a large and definitional impact on the total efficiency of flash flood mitigation (Tügel et al., 2020). Overall, infiltration systems have been studied and observed to be an effective means to mitigate flash flood risk. It should be noted that the same limiting factors that affect infiltration systems affect compact infiltration systems in similar ways. Overall, CISs have the potential to feature similar efficiencies that infiltration systems hold in regard to flood risk mitigation, but on a smaller, local scale with lower associated costs and maintenance.

Overall, the review of scholarly literature relating to the topic of urban flash flooding mitigation shows that flash flooding holds serious and increasing impacts (with regard to its sudden nature and increased intensity and frequency from climate change). This hazard is present within areas similar to Malta, which feature large portions of poorly planned, low-lying urban areas that are significantly susceptible to flash flood risk. It has also been shown that green infrastructure holds a positive relationship with urban flood risk decrease, through stormwater generation control. Despite the identification of this positive relationship, there are still knowledge gaps present within the total runoff reduction and peak flow reduction for green roof and compact infiltration systems (both individually and combined) that serve to be further studied and evaluated, especially within the Maltese context.

3. Methods

This project modelled green infrastructure combinations through one block of the urban zone in the vicinity of St. Aloysius College, with an area of approximately 8604 m². This block is located near a school where a CIS has been installed and holds similar geology, thus making it acceptable for CIS modelling. Similar to trends discussed above, this area is marked by dense urban development emphasised by many close housing buildings, impermeable surfaces, and little to no green space. Consequently, like much of Birkirkara, this study zone is at risk for flash flooding.

Through analysis using ArcGIS tools and Vatnor satellite imagery of 0.30 m resolution (taken on September 25th, 2025), 22 rooftops were identified in the study area, with areas ranging from 85 m² to 428m². The study area is provided below in Figure 1 and includes calculated area values. Additionally, an average rooftop area of 209 m² was identified and served as the basis on which the individual and combined GSI were analysed.



Figure 1. Characterisation of the study area in St. Aloysius, utilising Vatnor satellite data and ArcGIS with an emphasis on the approximation of rooftop area within the study area.

Within the model, four scenarios of proposed green infrastructure combinations were modeled for the average rooftop (209 m²) within the study area. These scenarios specifically simulate no new green infrastructure development (current state), green roof adoption, CIS adoption, and integrated green roof and CIS adoption. These differing infrastructure scenarios were modeled to evaluate how well they can control average storm events and flash flood events, as well as storms of increased rainfall intensities and temporal scales. The average storm characteristics were calculated based on 2024 rainfall data. Furthermore, intensification characteristics were calculated through standard deviations within the rainfall data. Finally, different sizes of rooftops and CIS storage tanks were also

assessed against the previously mentioned scenarios to identify specific efficiencies for differing building units. Through the model, stormwater generation reduction was generated for each storm event and mitigated by each scenario and assessed in terms of peak flow reduction and total runoff reduction. Overall, this project simulated how the proposed infrastructure scenarios can absorb and control runoff during current and escalated storm events. This project compares and evaluates proposed nature-based solutions in terms of their effectiveness at limiting stormwater generation within the selected study area.

This study began through the gathering and analysis of data regarding current experimental green roof and CIS projects within Malta, relevant geological and physical data regarding the geography and development within the selected study area, and current/escalated precipitation amounts for flash flooding events of differing intensity. All datasets were analysed to ensure reliability and applicability, with any uncertainties being noted for reference. Following data collection and analysis, relevant equations were utilised to generate runoff coefficients, dissipation rates, and other key GSI characteristics. These characteristics then served as the baseline when developing relationships within the model to accurately simulate the systems.

First, data from the experimental green roof project at the Ghajn Water Conservation Centre in Rabat, Malta, was obtained. The datasets analysed include rainfall data recorded in mm per m² on the 287 m² rooftop from January 2024 to July 2025 and runoff overflow data through four flow meters (measured in L) from the green roof from November 2024 to August 2025. These datasets were compared to find storm events that generated runoff values, thus resulting in only data from November 2024 to July 2025 being used in the analysis. Both of these datasets were recorded at a temporal resolution of 5 minutes. Additionally, the datasets showed some uncertainty toward the beginning until the flowmeters were artificially adjusted on the 11th of November. Consequently, no storms before this adjustment were considered for analysis.



Figure 2. Green roof in Ghajn Water Conservation Centre, in Rabat Malta. Characterised by approximately 3000 plants featuring differing rates of retention and unique characteristics that make them suitable for Malta's arid climate. Additionally, this green roof also hosts photovoltaic panels for solar energy harvest

Next, 17 rainfall events ranging from 11th November 2024 to 15th May 2025 were analysed, through which a variety of temporal scales, rainfall totals (mm), and runoff flows (L) were identified. Specifically, rainfall events were only considered if they produced runoff flow, with individual storm events being defined as continuous rainfall values with no break in rainfall for longer than an hour. Overall, time of storm event (minutes), time to runoff flow (minutes), time after rainfall (minutes), rainfall (mm), and runoff (L) were recorded for each analysed storm event. Time to runoff can be defined as the amount of time from the first instance of rainfall associated with a storm event to the first change in runoff flow, while time after rainfall is defined as the time from the last recorded rainfall value associated with a storm event to the time runoff flow stops generating.

Following the recording and calculation of relevant data from each storm event, all precipitation values were converted into cubic meters (m^3), and relevant equations were utilised to calculate runoff coefficients, rainfall intensities (m/min), and peak flow rates (m^3/min). Finally, averages for these values were calculated, notably producing an average runoff coefficient of 0.13 across the 17 rainfall events analysed, with associated time and rainfall intensity averages also being noted. When creating the green roof module within the model, the variables dictating runoff contribution (primarily variables which influenced the saturation level of the roof) were modelled so that, given the time and rainfall intensity averages recorded from the Ghajn dataset, a runoff coefficient of 0.13 would be produced. The variables dictating the saturation level and other nonlinear ratios developed from this scenario were kept constant to characterise the green roof.

In order to characterise the CIS within the model, data was obtained from the GEO-INF project. This data included tested dissipation rates, storage tank capacity, and borehole capacity for the ongoing CIS project located at St. Aloysius College. Originally, data loggers were positioned within and outside the CIS tanks in the study area to record pressure values and implicitly calculate values of water volume change over the course of two weeks. Following data collection, the dissipation rate of the CIS system was to be calculated. However, during the period of data collection, there was not enough rainfall/volume change to record any significant data and obtain changes in pressure for dissipation rate calculation. Resultingly, the dissipation rate obtained from initial tests by the GEO-INF project on installation was used as a baseline to develop accurate and adaptable relationships within the model. Specifically, the dissipation rate from tests referred to when the dissipation of CIS storage had reached capacity; thus, relevant equations were utilised to find an average rate at which groundwater dissipation occurs. Overall, data from the GEO-INF project served greatly to characterise the CIS within the model.

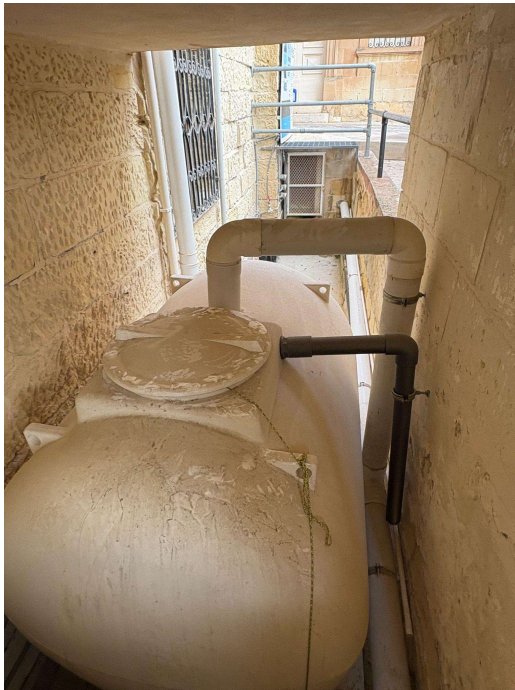


Figure 3. CIS in St. Aloysius college (GEO-INF) with a total storage capacity of 4.63 m^3 given the two storage tanks (2m^3 each) and the storage within the borehole itself. This system mitigates a catchment area of 640 m^2 and has been in operation since September 2023

Finally, precipitation data from 2024 were utilised to calculate average storm characteristics. This was done by cataloguing 69 storm events (given the same storm definitions utilised within the green roof data) and calculating associated averages. Furthermore, intensification characteristics (both in terms of increasing rainfall intensities and temporal scale) were calculated through the use of differing standard deviations

among the catalogued storm data. Overall, seven key storm events were developed from this data.

Table 1. A catalogue of analysed storms from April to December 2024, from obtained weather data. Total precipitation, rainfall intensity, flash flood status, and time are identified. Specifically, flash flood events are defined as storm events where the data began to record precipitation values on the scale of minutes instead of quarter hours.

Storm Event	Date	Total Precipitation (m)	Rainfall Intensity (mm/minute)	Flash Flood (Y/N)	Time (minutes)
1	4/16/2024	0.002	0.02	N	120
2	4/16/2024	0.002	0.04	N	75
3	4/19/2024	0.001	0.04	N	45
4	4/24/2024	0.013	0.04	N	375
5	4/24/2024	0.001	0.03	N	30
6	5/1/2024	0.020	0.15	N	79
7	5/1/2024	0.006	0.66	Y	10
8	5/1/2024	0.003	0.85	Y	5
...					
62	12/20/2024	0.001	0.04	N	30
63	12/20/2024	0.002	0.13	N	30
64	12/23/2024	0.002	0.02	N	120
65	12/23/2024	0.001	0.04	N	30
66	12/26/2024	0.003	0.13	N	41
67	12/26/2024	0.002	2.30	Y	1
68	12/27/2024	0.001	0.07	N	30
69	12/28/2024	0.001	0.05	N	30

Next, the model was developed through the use of key calculated or obtained values and characteristics that served as the basis for developed relationships. The primary generated data from the model includes total runoff reduction and peak flow reduction for each of the four infrastructure scenarios under seven unique storm events. Additionally, pink noise was used to generate realistic levels of randomness within the modelled storm events. The differing GSI scenarios were then further analysed under differing roof sizes and CIS capacity. Finally, all modelled outputs were recorded and compared to evaluate scenario performance in the reduction of stormwater generation, and used to influence recommendations regarding differing building characteristics and desired runoff contribution reduction.

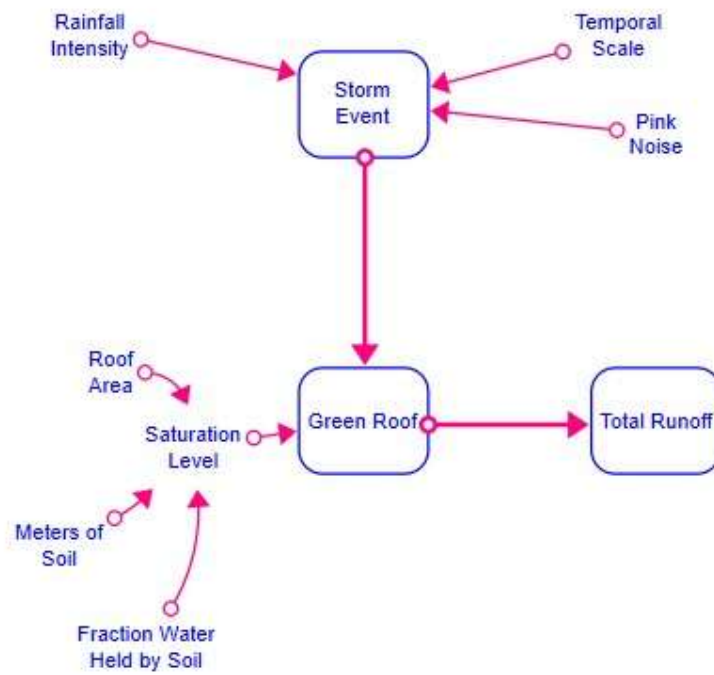


Figure 4. GSI scenario 2 (green roof) simplified model diagram

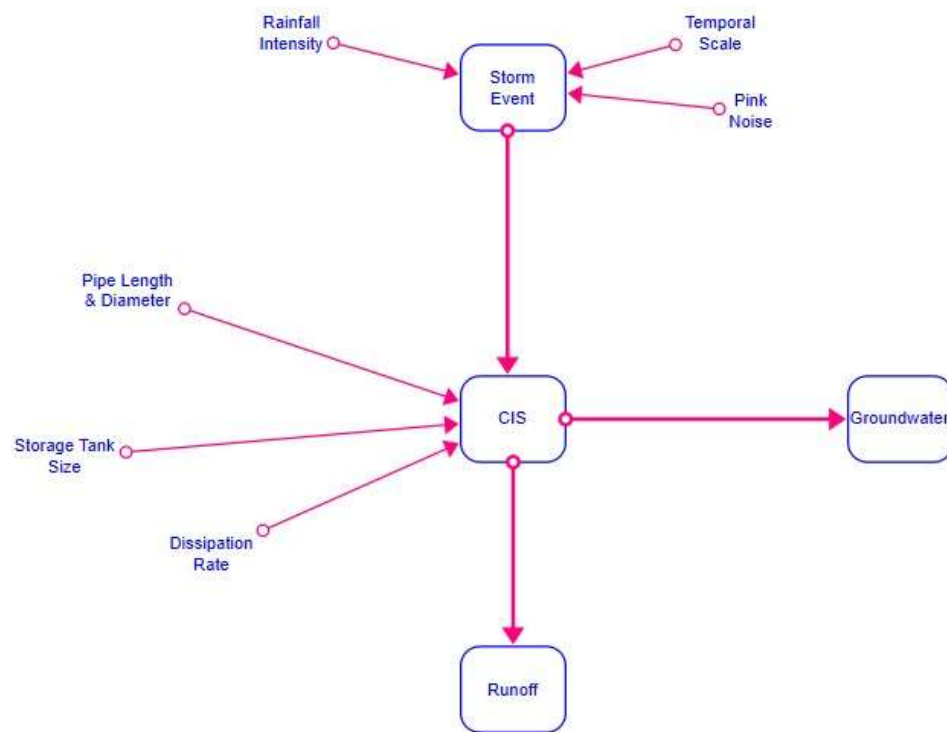


Figure 5. GSI Scenario 3 (CIS) simplified model diagram

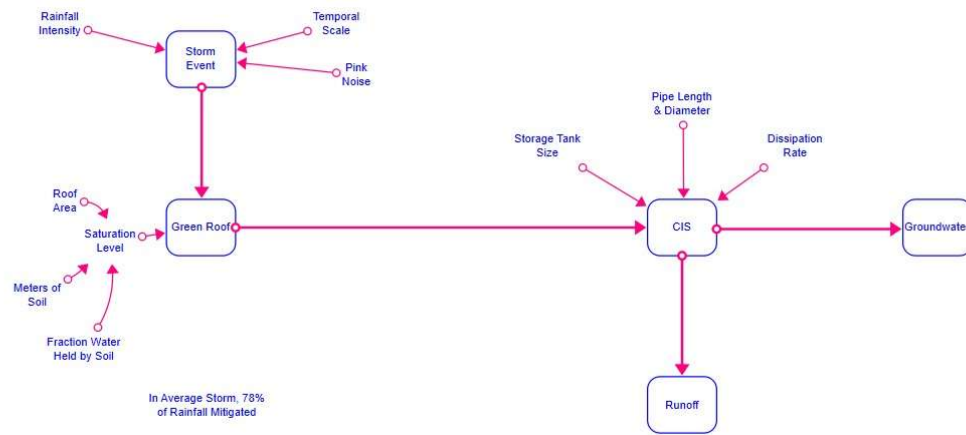


Figure 6. GSI Scenario 4 (combined green roof and CIS) simplified model diagram

As shown through the diagrams above, each modelled scenario features an input of rainfall generated from storm events that is transferred and held in stocks representing differing GSI types, before ultimately generating runoff when capacity is reached. The difference between total rainfall from a storm event and the total runoff generated represents the reduction impact of the GSI type. Additionally, these models are shown and documented in greater detail in the supporting information section of this study.

The storm type for this model is primarily defined by the input rainfall intensity, the temporal scale, and pink noise (utilised to capture the natural variability in rainfall). When simulating with the model, rainfall intensity and temporal scale should correspond with storm scenarios represented below. Next, as shown in Figure 2, the green roof and its capacity are primarily defined by its saturation level, which is defined by roof area, meters of soil, and water held in soil. As the roof becomes more saturated, more runoff begins to generate. This is consistent with the analysis of the Ghajn Green Roof project that the module is based on, as shown in Table 2 below. Next, the CIS stock and its capacity are defined primarily by physical size constraints, such as tank size and pipe measurements, as opposed to a constantly adapting saturation level. Consequently, this gives the CIS a rigid capacity that, when reached, creates rapid runoff generation. However, it should be noted that some water leaves to groundwater over time, as defined by the dissipation rate. Finally, scenario 4 (Figure 4) portrays the combined scenario of green roof and CIS, with both modules essentially functioning the same, except for the fact that the runoff from the green roof now inputs directly into the CIS module. Finally, the model generates values of total runoff reduction and peak flow rate reduction for each run scenario.

Overall, this project utilises secondary data from current green infrastructure projects, GIS satellite imagery, and weather data to model individual and combined green infrastructure systems' effectiveness at controlling flash flooding events of varying

intensities. The model compares the overall limitation of stormwater generation, as assessed through peak flow reduction and total runoff reduction values.

4. Results

4.1 Green Roof characterisation

In order to properly produce a model based on the Ghajn Green Roof Project, an analysis of key storms was conducted, as mentioned in the methodology above. These findings are displayed below in Table 2.

Table 2. Characterisation of several storm events in terms of time, total rainfall, runoff, runoff coefficient, specific timings of runoff, and rainfall intensity. These results were obtained specifically from the Ghajn Green Roof Project datasets

Storm Event 1	Time (min)	Total Rainfall (m ³)	Runoff (m ³)	Runoff Coefficient	Time to Runoff (min)	Time After Rainfall (min)	Rainfall Intensity (m/min)	Rainfall Intensity (mm/min)
1	165	2.07	0.22	0.11	70	5	4.36364E-05	0.044
2	670	30.36	0.18	0.01	440	80	0.00015791	0.158
3	520	7.12	0.57	0.08	270	35	4.76923E-05	0.048
4	5	0.40	0.17	0.42	230	255	0.00028	0.280
5	195	5.91	0.19	0.03	210	-60	0.000105641	0.106
6	275	10.22	1.22	0.12	75	10	0.000129455	0.129
7	140	2.53	0.01	0.00	115	-20	6.28571E-05	0.063
8	745	30.77	0.2	0.01	85	25	0.000143893	0.144
9	105	3.44	0.1	0.03	35	-30	0.000114286	0.114
10	145	4.94	0.59	0.12	40	70	0.000118621	0.119
11	315	7.69	2.86	0.37	155	160	8.50794E-05	0.085

12	225	1.89	0.04	0.02	165	-35	2.93333E-05	0.029
13	200	2.07	0.22	0.11	10	100	0.000036	0.036
14	480	13.43	4.33	0.32	40	105	0.0000975	0.098
15	400	3.16	0.58	0.18	330	20	0.0000275	0.028
16	405	8.15	1.83	0.22	5	35	7.01235E-05	0.070
17	105	1.26	0.08	0.06	65	-10	4.19048E-05	0.042
Average	300	7.97	0.79	0.13	138	44	9.36136E-05	0.094

4.2 CIS Characterisation

The CIS module was characterised given the measured dissipation rate of 2.65 L/min when the system was at full capacity. However, it is important to note that this dissipation rate is much lower than dissipation rates in other regions where CIS have been installed. This is due to the study unit's geology which features Lower Globigerina Limestone and therefore is much less favorable for higher dissipation (*Geology of the Maltese Islands - Final*, 2022). Given the measured size specifications of the CIS (M. Cremona, personal communication, March 30, 2026), shown below in Table 3, the total capacity (m³) of the system was calculated. Finally, given these measured and calculated values, relevant equations were utilised to find the specific dissipation rate of 0.000572 min⁻¹ which was utilised within the model to characterise the CIS module.

Table 3. St. Aloysius CIS GEO-INF installation measurements (M. Cremona, personal communication, March 30th, 2026). It is important to note that the first 5m of the borehole are cased, thus only allowing 15m available for infiltration. This has no impact on total storage and is done to protect basement structures

Measurements	Value	Units
Borehole Diameter	0.2	m
Borehole Depth	20	m

Storage Tank	2 (x2) = 4	m ³
Full System Dissipation Rate	2.65	Litres/min

Equation 6. Calculations for borehole volume, total system capacity, and average dissipation rate.

$$V = \pi \times r^2 \times h$$

$$V = \pi \times (0.2\text{m} \div 2)^2 \times (20\text{m})$$

$$V = 0.63\text{m}^3$$

$$\text{System Capacity} = \text{Total Tank Volume} + \text{Borehole Volume}$$

$$\text{SC} = (2\text{m}^3 \times 2) + (0.63\text{m}^3)$$

$$\text{SC} = 4.63\text{m}^3$$

$$\text{Specific Dissipation Rate} = \text{System Dissipation Rate} \div \text{System Capacity}$$

$$\text{Specific Dissipation Rate} = (2.65\text{L/min} \times 0.001\text{m}^3/\text{L}) \div (4.63\text{m}^3)$$

$$\text{Specific Dissipation Rate} = 0.000572 \text{ min}^{-1}$$

Table 4. Calculations from St. Aloysius CIS GEO INF installation measurements

Calculations	Value	Units
Borehole Capacity	0.630	m ³
System Capacity	4.630	m ³
Specific Dissipation Rate	0.000572	min ⁻¹

4.3 Storm Characterisation

As described above in the methodology, four proposed GSI scenarios were modeled to test their mitigative effectiveness in terms of total runoff reduction and peak flow

reduction. Each scenario was modelled against a variety of storm scenarios that emphasised differing rainfall intensities and storm timeframes, as shown in Table 5 below.

Table 5. The seven simulated storm events that each GSI type is tested against. Storm events 1 and 5 represent average storm events and flash flooding storm events, based on weather data, while all other storm events represent increases in either rainfall intensity or temporal scale. Finally, these storms were characterised specifically for the average roof size within the study area, thus the total rainfall refers to the amount generated on a 209 m² rooftop area

Storm Event	Time (min)	Rainfall Intensity (mm/min)	Total Rainfall (m³)	Peak Flow Rate (m³/min)
1	87	0.07	1.33	0.02
2	192	0.07	2.92	0.02
3	402	0.07	6.06	0.02
4	87	0.18	3.25	0.05
5	87	0.28	5.17	0.08
6	108	0.2	4.49	0.05
7	108	0.56	12.8	0.15

Storms one and six represent average storm events and average storm events featuring flash flooding characteristics (intense precipitation under short timeframes), respectively. Interestingly, the average storm event has a shorter amount of time than the average storm event associated with flash flooding characteristics. This is in part resulting from the fact that the average storm event includes all storm events, even those with very little rainfall over a short period of time, and also from the fact that some (but not all) flash flood events are associated with much longer overall storm events. Meanwhile, storms two and three, and storms four and five, represent increases upon the average storm event in terms of increasing temporal scale and rainfall intensity, respectively. Storms two and four represent an increase by one standard deviation of the dataset, while storms three and five represent an increase of three standard deviations of the dataset. Finally, storm seven represents a highly intensified version of the average storm event featuring flash flooding

characteristics, with a rainfall intensity nearly three times that of the average storm featuring flash flooding characteristics.

4.4 Runoff Mitigation

As shown through the tables below, all scenarios that include implementation of GSI configurations illustrated a large impact in terms of total runoff reduction and percentage runoff mitigation, as compared to the baseline scenario with no GSI implementation (Scenario 1).

Table 6. GSI scenario performance in terms of runoff reduction (m³) across a variety of storms on an average rooftop (209m²)

Storm Event	Scenario 1 (No GSI) (m³)	Scenario 2 (Green Roof GSI) (m³)	Scenario 3 (CIS GSI) (m³)	Scenario 4 (Green Roof & CIS GSI) (m³)
1	0	1.31	1.33	1.33
2	0	2.76	2.92	2.92
3	0	4.88	5.02	6.06
4	0	3.16	3.25	3.25
5	0	4.94	4.56	5.17
6	0	4.28	4.49	4.49
7	0	11.22	4.70	12.8

Table 7. GSI scenario performance in terms of percentage of total runoff reduction across a variety of storms on an average rooftop

Storm Event	Scenario 1 (No GSI) (m³)	Scenario 2 (Green Roof GSI) (m³)	Scenario 3 (CIS GSI) (m³)	Scenario 4 (Green Roof & CIS GSI) (m³)
1	0%	98%	100%	100%
2	0%	95%	100%	100%

3	0%	81%	83%	100%
4	0%	97%	100%	100%
5	0%	96%	88%	100%
6	0%	95%	100%	100%
7	0%	88%	37%	100%

However, the differing GSI scenarios showed a variety in terms of effectiveness when compared amongst each other. When modelled against the average storm (storm one), all GSI configurations mitigated large percentages, with both scenarios utilising CIS mitigating 100% of the runoff generated by the storm. However, as the storms intensified, scenario 3 showed noticeable drops in mitigative effectiveness, while scenario 2 held greater resilience to the variety of storms. This is evidenced by the runoff reduction percentages present within storm seven, featuring a 51% difference between scenario 2 and scenario 3. The clear standout of the compared scenarios is scenario 4, which features a combination of green roof and CIS GSIs. Across all storms, this scenario mitigated 100% of all runoff, resulting in the greatest runoff reduction efficiency across the variety of storms.

4.5 Peak Flow Reduction

In many ways, the results regarding peak flow reduction show similar trends to the results of runoff reduction. These include trends of higher amounts of peak flow reduction being exhibited by the scenarios utilising GSI and by CIS exhibiting greater peak flow reduction than green roof GSI during storms where capacity was not reached. However, in scenarios where capacity is reached, scenario 3 illustrates sharp declines in peak flow reduction, especially when compared to scenario 2. Meanwhile, scenario 4 continued to feature total (100%) reductions in terms of peak flow rate.

Table 8. GSI scenario performance in terms of peak flow rate reduction (m^3/min) across a variety of storm events

Storm Event	Scenario 1 (No GSI) (m^3)	Scenario 2 (Green Roof GSI) (m^3)	Scenario 3 (CIS GSI) (m^3)	Scenario 4 (Green Roof & CIS GSI) (m^3)
1	0.000	0.018	0.019	0.019

2	0.000	0.017	0.019	0.019
3	0.000	0.012	0.004	0.019
4	0.000	0.044	0.047	0.047
5	0.000	0.067	0.013	0.075
6	0.000	0.047	0.053	0.053
7	0.000	0.112	0.012	0.151

Despite higher values in storms where its capacity was not reached, scenario 3 featured low peak flow reductions in several storms such as storm events three, five, and seven. This shows a clear weakness toward storms featuring flash flooding characteristics. In contrast, scenario two showed greater resilience in terms of peak flow reduction, with six out of seven storms featuring peak flow reduction percentages of 74% or above. However, storm three (with the largest timeframe), exhibited a 64% reduction percentage, thus showing a clear weakness to storms of larger temporal scales. Despite this, the reduction percentage for this storm and others (where CIS capacity was not reached), was still higher than that of scenario 3.

Table 9. GSI scenario performance in terms of percentage reduction of peak flow rate across a variety of storms

Storm Event	Scenario 1 (No GSI)	Scenario 2 (Green Roof GSI)	Scenario 3 (CIS GSI)	Scenario 4 (Green Roof & CIS GSI)
1	0%	95%	100%	100%
2	0%	90%	100%	100%
3	0%	64%	23%	100%
4	0%	94%	100%	100%
5	0%	89%	18%	100%

6	0%	89%	100%	100%
7	0%	74%	8%	100%

Overall, scenario 4 still had the greatest impact in mitigating peak flow. However, the green roofs showed a trend of greater resilience and overall greater peak flow mitigation as compared to CIS, specifically in cases where the CIS capacity was reached. This further emphasises that green roofs show greater resilience to storms of a larger intensity. This is exemplified in figures 7 and 8, by the smaller flow rates and delayed peak flow rates present within scenario 2 as compared to scenario 3.

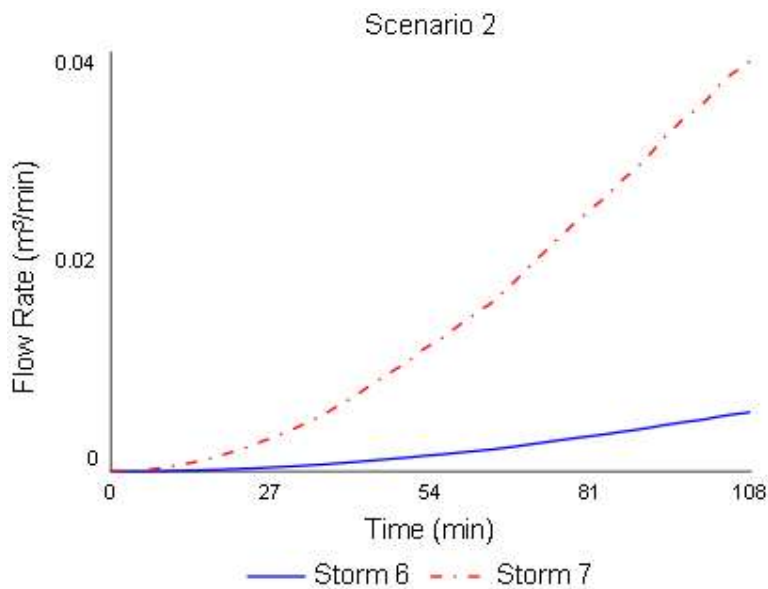


Figure 7. Scenario 2 flow rates for storms six and seven

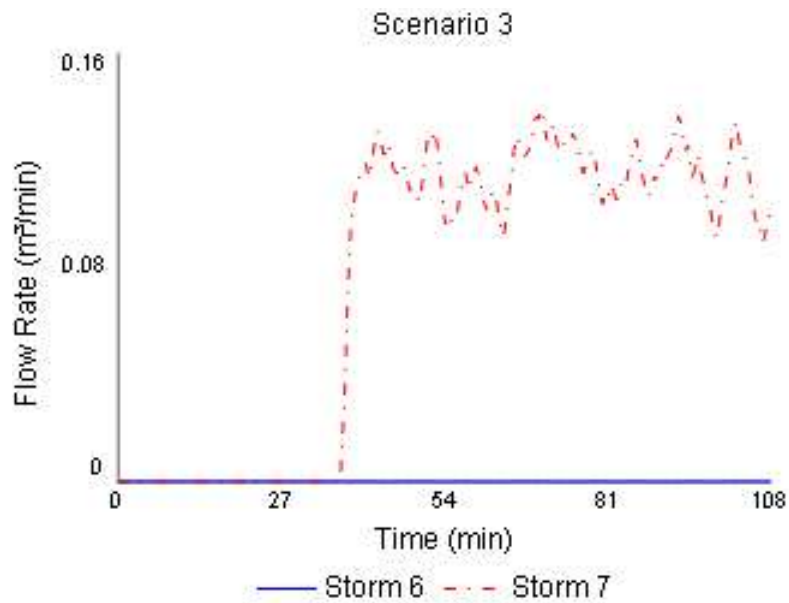


Figure 8. Scenario 3 flow rates for storms six and seven

4.6 Further Optimisation

Next, the integrated green roof and CIS configuration was modelled against differing roof sizes that emphasised smaller and larger roof sizes (as well as the average roof size utilised for previous calculations) in order to assess the effect of roof size on mitigation potential.

Table 10. Reduction percentages for both peak flow and runoff across differing roof sizes utilising scenario 4, modeled against storm seven.

roof sizes	123 (m ²)	209 (m ²)	294 (m ²)
Peak Flow Reduction Percentage	100%	100%	100%
Runoff Reduction Percentage	100%	100%	100%

Table 11. Reduction Percentages for both peak flow and runoff across differing roof sizes utilising scenario 2, modeled against storm seven.

roof sizes	123 (m ²)	209 (m ²)	294 (m ²)
Peak Flow Reduction Percentage	74%	74%	74%
Runoff Reduction Percentage	88%	88%	88%

As displayed in Table 10, scenario 4 continued to show mitigative prowess in terms of peak flow and total runoff reduction, with 100% reductions across all differing roof sizes. Also, scenario 2 showed no impact from differing roof sizes with static percentages across the variety, as shown in Table 11. This is to be expected as the green roof's absorption capabilities are directly influenced by the area of the rooftop, thus while an increase in roof area creates an increase in rainfall accumulation it also creates an increase in rainfall absorption within this GSI. This trait likely influenced scenario 4's effectiveness as well.

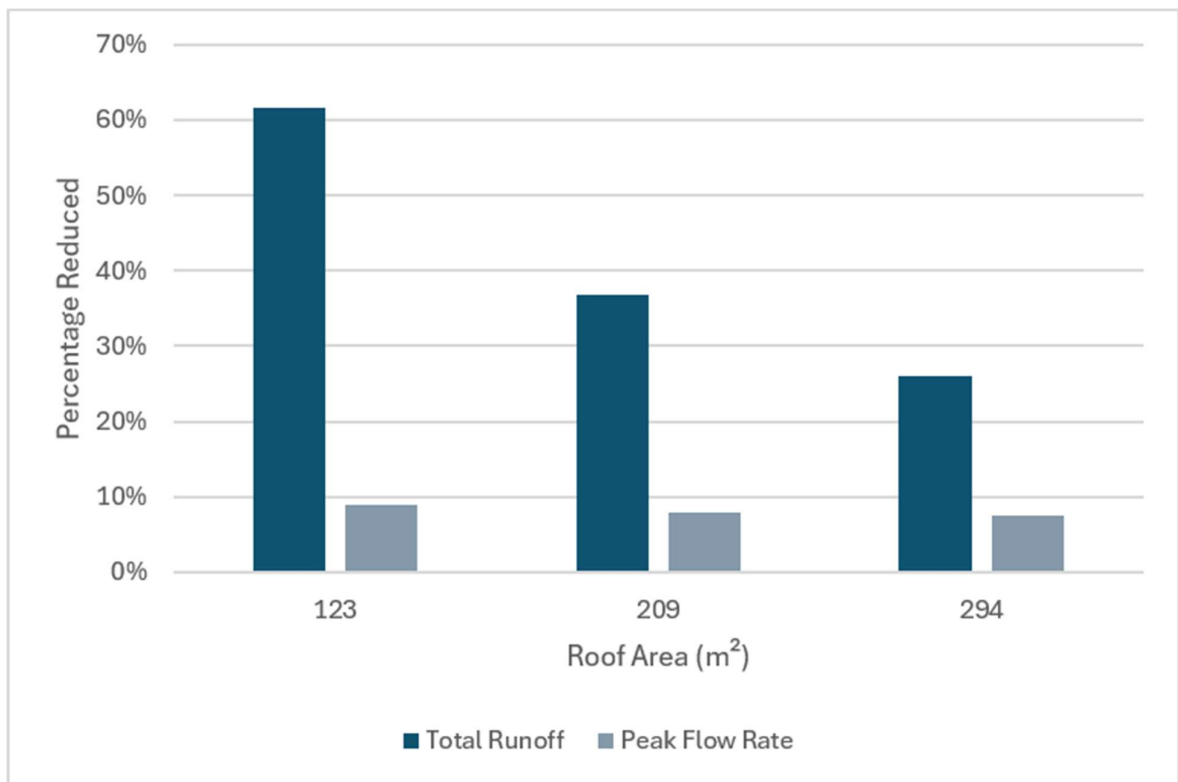


Figure 9. Percentage reduction for both total runoff and peak flow rate across differing roof sizes, specifically modelled with GSI scenario 3 against storm seven.

As shown above in Figure 9, runoff reduction percentages feature a negative relationship with roof area increase, under scenario 3. However, peak flow reduction was only marginally affected by the differing roof sizes.

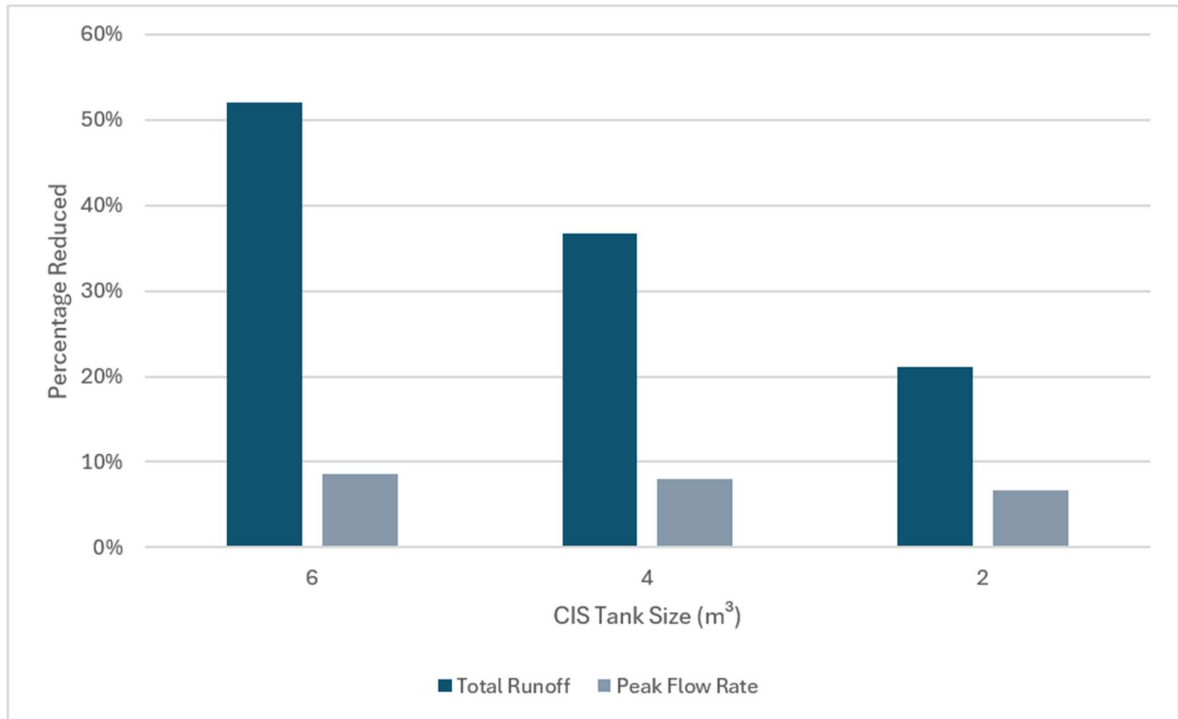


Figure 10. Percentage reduction for both total runoff and peak flow rate across differing CIS tank sizes, specifically modelled with GSI scenario 3 against storm seven.

Next as portrayed in figure 10, CIS tank size increase held a positive relationship with runoff reduction percentage, especially apparent when analysed through scenario 3. Peak flow rate reduction also held a similar relationship to CIS tank size increase but to a smaller and somewhat marginal degree.

Table 12. Percentage reduction of both peak flow rate and runoff across a decreasing CIS tank sizes modeled in scenario 4, against storm seven

CIS Tank Sizes	4 (m³)	2 (m³)	1 (m³)	0.5 (m³)	0.25 (m³)
Peak Flow Reduction Percentage	100%	100%	93%	75%	75%
Runoff Reduction Percentage	100%	100%	100%	96%	95%

Finally, scenario 4 was analysed with a larger variety of tank sizes that emphasised smaller tank sizes. Mitigative effectiveness of scenario 4, is evidenced through Table 12 as total mitigation percentages held even during 2 m³ decrease in tank size. Interestingly, peak

flow reduction suffered a 25% decrease from the 2 m³ to 0.5 m³ tank size but held steady as the tank size continued to decrease (be it by smaller values). The potential of smaller tank sizes under this scenario is evidenced through both peak flow rate and total runoff reduction percentages not dropping under 90%, across all tank size configurations, even with 0.25 m³ tank size.

5. Discussion

Besides the obvious trend of combined green roof and CIS dominance, the results shown above illuminate many implications regarding the use and implementation of differing GSI configurations. These implications primarily result from the limitations of CIS's capacity, the resilience found within green roofs during a variety of storms, and the impacts of roof sizing and CIS tank sizes on differing GSI types. First, as shown through weaker percentages of mitigation during key intense storms, CIS has clear limits once capacity has been reached. This weakness is evidenced by diminishing reduction percentages found across several storms in terms of total runoff and especially peak flow rate. This trend among peak flow rates shows an impact similar to that of a dam or levee breaking, whereby once CIS reaches capacity and no longer effectively mitigates the storm, there is actually an increase in peak flow. The CIS would not definitionally suffer damages from the storm like grey infrastructure would, so the infrastructure is overall still more effective than grey infrastructure traditionally used. This capacity is dictated primarily through tank size, but also through the groundwater dissipation rate. It must also be mentioned that the groundwater dissipation effect has direct positive impacts on groundwater recharge and overall water supply. As shown through the results above, changes in tank sizes can delay this limitation. However, an increase in the groundwater dissipation rate shows the highest potential in actually reducing this limitation among all storms (while also increasing water supply). Fortunately, the geology in many other regions across Malta produces higher dissipation rates than the Lower Globigerina Limestone found within the study area, therefore higher dissipation rates can be assumed in other Maltese regions and the dissipation rate within this study can be seen as a worst-case scenario.

Next, while green roofs showed relatively lower mitigation values in scenarios where CIS capacity was not reached (storms of less temporal length / rainfall intensity), they presented greater values during more intense storms where capacity was reached scenario 3. Green roofs greatly reduced the time to reach peak flow. Overall, this shows greater resilience and flexibility to a wider variety of storms, as opposed to other GSI. Additionally, results were collected regarding time till runoff began and time until runoff stopped (after the storm event had ended), and while these were not utilised in the model, they show significant potential regarding future studies and should be explored. However, it must also be noted that while green roofs do show significant potential, they also feature significantly higher investment and maintenance costs when compared to CIS systems, especially given Malta's semi-arid environment. Consequently, while green roofs did hold higher reduction values and percentages, high maintenance and implementation costs as well as space requirements, CIS may still be more feasible for widespread adoption within Malta.

Finally, differing roof sizes show clear differences in the extent and type of GSI necessary for successful flooding mitigation. These differences had powerful impacts when combined with changes in CIS tank size, especially shown through combinations made for scenario 4 under differing roof sizes. Overall, these reductions present within differing roof sizes and CIS tank sizes show clear opportunities for reductions in implementation efforts and costs. These differences influenced the following list of GSI recommendations for different roof sizes which emphasises reductions in implementation needs and cost (both through smaller CIS tank sizes and differing GSI types for different roof sizes). Below, several GSI configurations are recommended for each roof size, to portray a range that emphasises the tradeoff between total risk reduction and potential costs of implementation and maintenance.

5.1 GSI Recommendations

Due to lighter needs, the following GSI types are recommended for the smaller roof size (123m²). All recommended GSI types hold great potential for runoff and peak flow rate reduction, with scenario 4 (modified with 0.5 m² tank size) holding complete mitigation across all storm events. However, it must also be noted that within the recommendations for the smaller roof sizes (and other roof sizes) that scenario 3 presents much lower peak flow rate reductions when CIS capacity is reached (mitigation drops below 100%).

Table 13. Runoff mitigation percentages across differing storms for GSI types recommended for 123 m² Roof. From left to the right recommendations emphasise greater runoff control, as evidenced by the increasing percentages.

Storm Event	Scenario 3 (6 m³ tank size)	Scenario 2	Scenario 4 (0.25 m³ tank size)	Scenario 4 (0.5 m³ tank size)
1	100%	98%	100%	100%
2	100%	95%	100%	100%
3	100%	81%	100%	100%
4	100%	97%	100%	100%
5	100%	96%	100%	100%
6	100%	95%	100%	100%
7	87%	88%	99%	100%

Next, for rooftops of average area (209 m²), GSI types shown in Table 14 are recommended for use. Scenario 4 (modified with 2 m² tank size) features complete mitigation of all storm events.

Table 14. Runoff mitigation percentages across differing storms for GSI types recommended for 209 m² Roof. From left to the right recommendations emphasise greater runoff control, as evidenced by the increasing percentages.

Storm Event	Scenario 3 (6 m³ tank size)	Scenario 2	Scenario 4 (1 m³ tank size)
1	100%	98%	100%
2	100%	95%	100%
3	100%	81%	100%
4	100%	97%	100%
5	100%	96%	100%
6	100%	95%	100%
7	52%	88%	100%

Finally, for rooftops of larger area (294 m²) the following GSI types shown in Table 15 are recommended. Similar to the average rooftop, scenario 4 (modified with 2 m²) fully mitigates all storm events.

Table 15. Runoff mitigation percentages across differing storms for GSI types recommended for 294 m² Roof. From left to the right recommendations emphasise greater runoff control, as evidenced by the increasing percentages.

Storm Event	Scenario 3 (6 m³ tank size)	Scenario 2	Scenario 4 (1 m³ tank size)	Scenario 4 (2 m³ tank size)

1	100%	98%	100%	100%
2	100%	95%	100%	100%
3	84%	81%	100%	100%
4	100%	97%	100%	100%
5	89%	96%	100%	100%
6	100%	95%	100%	100%
7	37%	88%	95%	100%

As mentioned above, several GSI configurations are represented, thus showing the differences in total mitigation effectiveness (with more effective types presented on the right of the tables). Optimisations were pursued in the form of reductions in tank size and the inclusion of GSI types that hold less in costs and efforts of implementation. These different options are important as there is a clear tradeoff between total mitigation effectiveness and the costs/efforts associated with greater GSI use. Individuals and communities hold different levels of resources for investment into these GSI types; thus, while it is important to research the greatest mitigation effectiveness, it is also important to research the greatest mitigation effectiveness available given the least amount of GSI implementation necessary. In fact, this research was conducted to discover alternatives to rainwater cisterns, which are not consistently implemented due to not only a lack of enforcement, but also underlying behavior relating to the avoidance of higher costs/efforts of maintenance and implementation. Additionally, size requirements for rainwater cisterns (as mentioned in background) could potentially be reduced if the rainwater cistern was linked with a CIS system. This would require inaccessible roofs and water not be utilised for second class purposes, but would contribute heavily toward groundwater recharge and peak flow reduction, thus making it a powerful retrofit solution for developments without a cistern installed.

So, while these GSI types do provide an alternative to rainwater cisterns, it must be ensured that this GSI does not fall into similar pitfalls of high expenses of implementation and maintenance that led to the inconsistent use of rainwater cisterns within the study area. Overall, further research should emphasise not only higher effectiveness in GSI flood mitigation, but also ways to produce higher effectiveness in flood mitigation given the lowest necessary GSI implementation.

5.2 Limitations of Study and Recommendations for Future Work

This study faced several limitations that impacted the scope and depth of this work, primarily resulting from the short timeframe of the study. These limitations resulted in a larger use of secondary data as opposed to primary data, with the failure in CIS primary data, due to a lack of rainfall collection serving as evidence of this trend. Additionally, it is important to note that secondary data utilised was primarily from relatively new experiment projects, thus limiting the total amount of data available. The scope of this study also primarily focused on reduction of peak flow rates and total runoff values. Consequently, timeframes regarding runoff start and end (in relation to storm events), economic burdens associated with GSI, and improvements on dissipation rate of CIS were not within the focus of this study. Future research should explore these topics in greater depth. Specifically, timeframes of runoff for individual and combined GSI types should be explored and utilised to a greater degree in model creation. Secondly, comparative costs of the GSI types in terms of implementation and maintenance should be researched further, especially in terms of quantifying the irrigation needs of green roofs during the dry session in Malta. Finally, dissipation rates should be explored across differing geologies and the impact of differing borehole diameter and depth on dissipation rates should be researched further.

6. Conclusions

Overall, all modelled GSI types serve as powerful alternatives to rainwater cisterns and other infrastructural types, in terms of runoff and peak flow reduction. While CIS in general proved to be more effective than green roofs in overall runoff contribution mitigation during average and less intense storms, it also featured lower effectiveness and ultimately greater failure during storms where the capacity of the GSI was reached. Therefore, green roofs have greater adaptability and resilience, while CIS hold higher rates of mitigation in storms where their capacity is not reached. However, the combination of green roof and CIS GSI truly stood out at holding the greatest effectiveness, resilience, and adaptability at mitigating the runoff contributions and peak flow rates of a variety of storms. The further optimised recommendations for specific roof sizes and differing tank sizes were used to further demonstrate the mitigative potential of combined green roof and CIS GSI both in terms of peak flow rate and total runoff reduction. While all GSI types hold their own tradeoffs in terms of costs/efforts of implementation/maintenance and resilience to storm events, this study yields greater information to assess these tradeoffs through the simulated peak flow reduction and total runoff reduction values.

These results are especially important for the Maltese context due to a variety of factors including the exceptional risk of flash flooding events within urban areas, the historical difficulties in water management and urban planning, and the inconsistent enforcement of rainwater mitigation measures (as evidenced through the lack of rainwater cisterns within Birkirkara and many other areas). This study and the associated findings present potential pathways for addressing flash flood risks, new information to influence water management and urban planning frameworks, and useful alternatives to expensive and sometimes ineffective adaptation measures. Of special importance is the fact that these findings address knowledge gaps present within known literature regarding these GSI types and could serve as an influence for the GSI manual and other documents associated with Maltese water management.

Ultimately, anthropogenic drivers associated with climate change are forcing the intensity and frequency of flash flooding events to increase. While mitigation efforts to decrease anthropogenic climate change forcing are of paramount importance, a certain amount of climate change impacts will be felt over the coming decades due to time delays within the Earth system. Consequently, adaptation measures are essential in order to decrease the potential harm and costs associated with climate change. These researched GSI types represent a pathway to take greater control of coming climate change impacts and ultimately reduce the future harms and costs incurred by individuals, businesses, and the governments within low-lying urban areas prone to flash flooding within Malta and beyond.

7. References

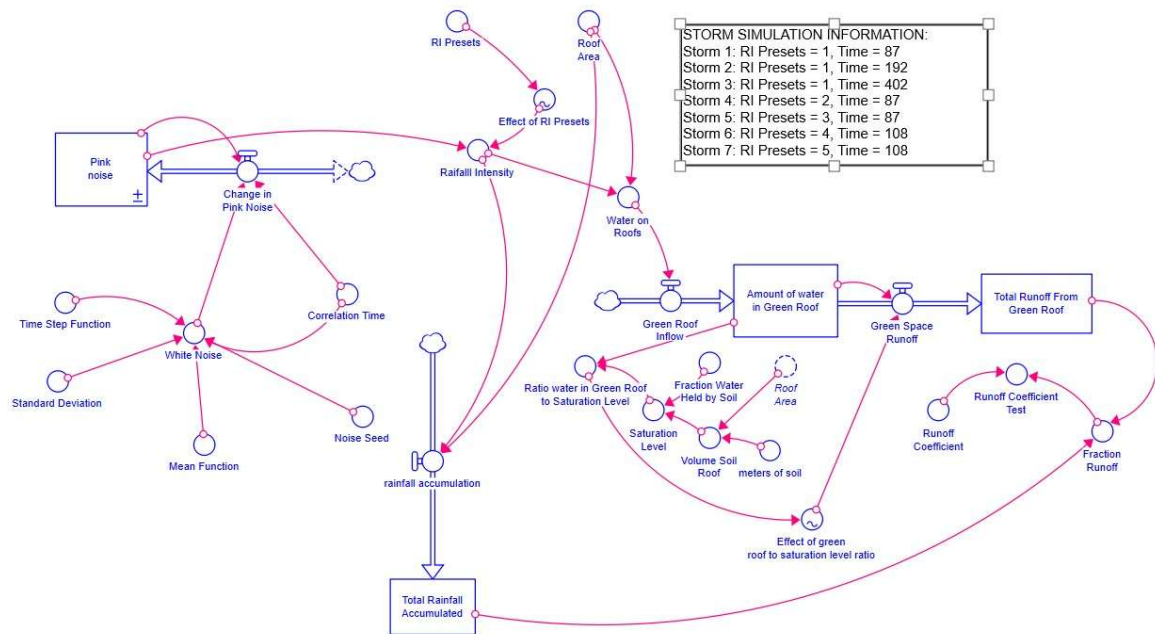
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8. Supporting Information, Model Documentation

8.1 Scenario 2 Model

This model simulates the hydrological behavior of a green roof system under varying rainfall conditions, helping to evaluate water retention efficiency and runoff mitigation performance. It translates dynamic precipitation inputs into runoff outputs by modeling the interactions between roof dimensions, soil storage dynamics, and drainage behavior.



Total	Count	Including Array Elements
Variables	29	29
Stocks	4	4
Flows	4	4
Converters	21	21
Constants	10	10
Equations	15	15
Graphicals	2	2

Equation	Properties	Units	Documentation	Annotation

Top-Level Model:						
	Amount_of_water_in_Green_Roof(t)	Amount_of_water_in_Green_Roof(t - dt) + (Green_Roof_Inflow - Green_Space_Runoff) * dt	INIT Amount_of_water_in_Green_Roof = 0	m ³	A stock variable that accumulates and tracks the volume of water currently stored within the green roof substrate. It increases via the Green Roof Inflow and is depleted over time by the Green Space Runoff.	NON-NEGATIVE
	Pink_noise(t)	Pink_noise(t - dt) + (Change_in_Pink_Noise) * dt	INIT Pink_noise = Mean_Function	Dimensions	A stock tracking an auto-correlated stochastic signal used to represent realistic, fluctuating weather patterns. It starts at the Mean Function value and changes dynamically according to the Change in Pink Noise flow.	
	Total_Rainfall_Accumulated(t)	Total_Rainfall_Accumulated(t - dt) + (rainfall_accumulation) * dt	INIT Total_Rainfall_Accumulated = 0	m ³	A stock variable that accumulates the total volumetric water input on the entire roof surface over time, fed by the rainfall accumulation flow.	NON-NEGATIVE
	Total_Runoff_From_Green_Roof(t)	Total_Runoff_From_Green_Roof(t - dt) + (Green_Space_Runoff) * dt	INIT Total_Runoff_From_Green_Roof = 0	m ³	A stock variable that accumulates the total volume of water discharged from the green roof system as runoff over time, fed directly by the Green Space Runoff flow.	NON-NEGATIVE
	Change_in_Pink_Noise	(White_Noise - Pink_noise)/Correlation_Time		Per Minute	The flow regulating the update rate of the Pink Noise stock. It is calculated as the difference between the current White Noise and Pink Noise divided by the Correlation Time.	
	Green_Roof_Inflow	Water_on_Roofs		m ³ /min	The volumetric rate of water entering the green roof system from the roof surface per minute. It is determined by the total Water on Roofs	UNIFLOW
	Green_Space_Runoff	Amount_of_water_in_Green_Roof*Effect_of_green_roof_to_saturation_level_ratio		m ³ /min	The flow rate of outflowing from the green roof per minute. It is modeled dynamically as the product of the current Amount of Water in Green Roof and the non-linear drainage coefficient determined by the Effect of Green Space to Saturation.	UNIFLOW
	rainfall_accumulation	Rainfall_Intensity*Roof_Area		m ³ /min	A flow representing the volume of water landing on the total roof area per minute, calculated as the product of Rainfall Intensity and Roof Area.	UNIFLOW

☐	Correlation_Time	1		Years	A constant parameter set to 1 year that determines the temporal memory or persistence of the pink noise weather generator, controlling how rapidly the stochastic rainfall patterns fluctuate.	
☐	Effect_of_green_roof_to_saturation_level_ratio	GRAPH(Ratio_water_in_Green_Roof_to_Saturation_Level) Points: (0.000, 0.0000), (0.200, 0.0200), (0.400, 0.0400), (0.600, 0.0600), (0.800, 0.0800), (1.000, 0.1200), (1.200, 0.2100), (1.400, 0.4050), (1.600, 0.5000), (1.800, 0.5000), (2.000, 0.5000)		Dimensionless/m	A graphical function that translates the current water ratio into a dynamic drainage rate multiplier. It represents how physical saturation increases the rate of gravity drainage as the soil becomes wetter.	
☐	Effect_of_RI_Presets	GRAPH(RI_Presets) Points: (0.000, 0), (1.000, 0.00007159), (2.000, 0.00017522), (3.000, 0.000278845), (4.000, 0.000196), (5.000, 0.00056), (6.000, 0.0000782)		m/min	A graphical function that maps the selected preset index to a specific precipitation magnitude in meters per minute, allowing users to test standardised storm profiles.	
☐	Fraction_Runoff	Total_Runoff_From_Green_Roof/Total_Rainfall_Accumulated		Dimensionless	A dynamic performance indicator calculated as the ratio of Total Runoff From the Green Roof to the Total Rainfall. It measures the net retention efficiency of the green roof design.	
☐	Fraction_Water_Held_by_Soil	0.7		Dimensionless	A constant parameter representing the porosity and effective retention capacity of the soil, set to 0.7 (70% of soil volume can hold water).	
☐	Mean_Function	1		Dimensionless	A constant parameter set to 1.0 dimensionless units which serves as the baseline, average level around which the stochastic white and pink noise components oscillate.	
☐	meters_of_soil	2.2		m	A constant parameter defining the physical depth of the soil substrate on the green roof, set to 2.2 meters.	
☐	Noise_Seed	7		Dimensionless	A constant parameter set to 7 that initialises the pseudo-random number generator for the White Noise calculation, ensuring simulation run repeatability.	
☐	Rainfall_Intensity	Effect_of_RI_Presets*Pink_noise		m/min	Represents the rate of precipitation falling per unit time, measured in meters per minute. It is calculated using a conditional equation based on current simulation time, combining the raw pink noise generation with the preset scenario multipliers..	

○	Ratio_water_in_Green_Roof_to_Saturation_Level	Amount_of_water_in_Green_Roof/Saturation_Level		Dimensionless	A dimensionless index representing how close the green roof soil is to its total water holding capacity. It is calculated as the ratio of the current Amount of Water in the Green Roof to the Saturation Level.	
○	RI_Presets	1		Dimensionless	An integer-based index switch set to 1, used as an input to the graphical function to select between different predefined storm or rainfall intensity profiles.	
○	Roof_Area	209		m ²	A constant parameter representing the total structural surface area of the roof, set to 209 square meters. It serves as a geometric multiplier to convert raw linear rainfall depth into volumetric water flow rates and to determine the physical dimensions of the soil layer.	
○	Runoff_Coefficient	0.13		Dimensionless	A constant empirical parameter set to 0.13, representing the standard fraction of rainfall that is expected to become runoff on a conventional roof surface for validation purposes.	
○	Runoff_Coefficient_Test	Fraction_Runoff/Runoff_Coefficient		Dimensionless	An evaluation variable used to compare the observed Fraction Runoff during simulation against the empirical baseline Runoff Coefficient parameter.	
○	Saturation_Level	Volume_Soil_Roof*Fraction_Water_Held_by_Soil		m ³	The maximum capacity of water that the green roof's soil layer can hold, measured in cubic meters. It is calculated as the total Volume of Soil on the Roof multiplied by the Fraction of Water Held by the Soil.	
○	Standard_Deviation	.1		Dimensionless	A constant parameter set to 0.1 dimensionless units that defines the variability and spread of the random fluctuations generated by the White Noise equation.	
○	Time_Step_Function	DT		Years	A variable representing the simulation time step size (DT) converted to units of years, helping to maintain dimensional consistency in the stochastic noise equations.	
○	Volume_Soil_Roof	meters_of_soil*Roof_Area		m ³	Calculates the total physical volume of the soil substrate by multiplying the meters of soil depth by the overall Roof Area.	

	Water_on_Roofs	Roof_Area*Rainfall_Intensity		m ³ /min	Calculates the total volumetric flow of rainwater falling onto the roof surface per minute. It is calculated as the direct product of the Roof Area and the current Rainfall Intensity.	
	White_Noise	Mean_Function+Standard_Deviation*((24*Correlation_Time/Time_Step_Function)^0.5*(RANDOM(-0.5, 0.5, Noise_Seed)))		Dimensions	A variable that generates uncorrelated random values at each time step, centered around the Mean Function. It uses a random distribution scaled by the Standard Deviation, Correlation Time, and Time Step Function.	

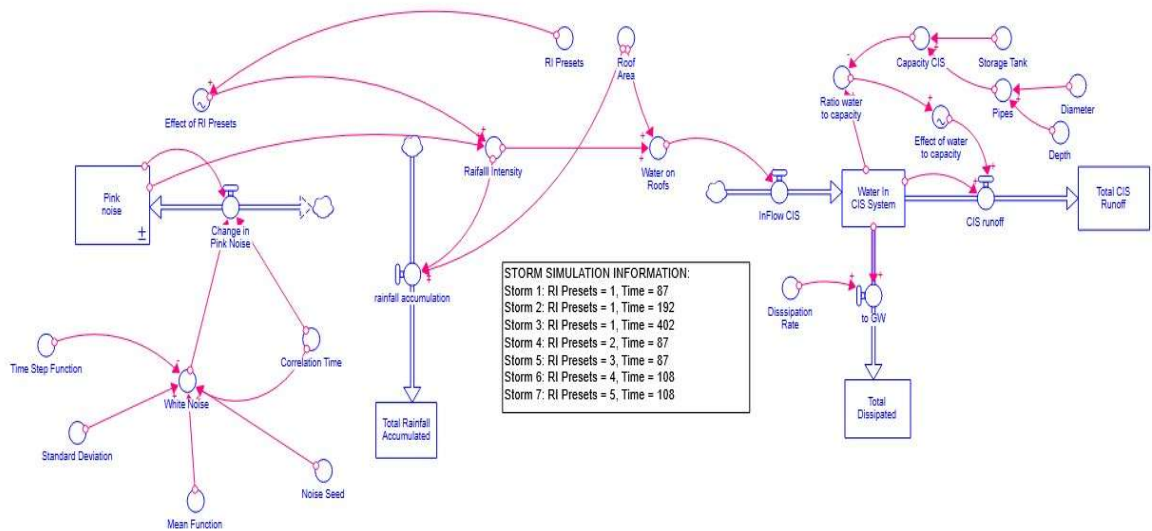
STORM SIMULATION INFORMATION:
Storm 1: RI Presets = 1, Time = 87
Storm 2: RI Presets = 1, Time = 192
Storm 3: RI Presets = 1, Time = 402
Storm 4: RI Presets = 2, Time = 87
Storm 5: RI Presets = 3, Time = 87
Storm 6: RI Presets = 4, Time = 108
Storm 7: RI Presets = 5, Time = 108

Run Specs	
Start Time	0
Stop Time	87
DT	0.25
Fractional DT	False
Save Interval	0.25
Sim Duration	1.5
Time Units	Min
Pause Interval	0
Integration Method	Euler

Keep all variable results	True
Run By	Run
Calculate loop dominance information	True
Exhaustive Search Threshold	1000

8.2 Scenario 3 Model

This model preserves all original variables and structures, implementing the feedback loops for the Combined Infiltration-Storage (CIS) system. Rainfall is simulated using a pink noise algorithm that alters the intensity. This rainwater accumulates from roof surfaces into a storage system composed of storage tanks and pipes. Once the storage approaches capacity limits, a non-linear threshold effect is activated, forcing a dramatic increase in spillover runoff, which is accumulated in the total runoff stock.



Total	Count	Including Array Elements
Variables	29	29
Stocks	5	5

Flows	5	5
Converters	19	19
Constants	10	10
Equations	14	14
Graphicals	2	2

	Equation		Properties	Units	Documentation	Annotation
Top-Level Model:						
	Pink_noise(t)	$Pink_noise(t - dt) + (Change_in_Pink_Noise) * dt$	INIT Pink_noise = Mean_Function	Dimensionless	Pink noise state used for random variations.	
	Total_CIS_Runoff(t)	$Total_CIS_Runoff(t - dt) + (CIS_runoff) * dt$	INIT Total_CIS_Runoff = 0	m^3	Accumulates runoff that spills over.	NON-NEGATIVE
	Total_Dissipated(t)	$Total_Dissipated(t - dt) + (to_GW) * dt$	INIT Total_Dissipated = 0	m^3	Total amount of water that has drained to groundwater.	NON-NEGATIVE
	Total_Rainfall_Accumulated(t)	$Total_Rainfall_Accumulated(t - dt) + (rainfall_accumulation) * dt$	INIT Total_Rainfall_Accumulated = 0	m^3	Cumulative sum of all precipitation accumulated.	NON-NEGATIVE
	Water_In_CIS_System(t)	$Water_In_CIS_System(t - dt) + (InFlow_CIS - to_GW - CIS_runoff) * dt$	INIT Water_In_CIS_System = 0	m^3	The amount of water stored inside the CIS.	NON-NEGATIVE
	Change_in_Pink_Noise	$(White_Noise - Pink_noise) / Correlation_Time$		Per Minute	Calculates the change in pink noise to approach white noise.	
	CIS_runoff	$Effect_of_water_to_capacity * Water_In_CIS_System$	OUTFLOW PRIORITY: 2	m^3/min	Runoff generated from the CIS once capacity thresholds are breached.	UNIFLOW
	InFlow_CIS	Water_on_Roofs		m^3/min	Inflow into the cis system, directly from water on roofs	UNIFLOW

	rainfall_accumulation	Raifalll_Intensity*Roof_Area		m ³ /min	Flow of incoming rainfall accumulation.	UNIFLOW
	to_GW	Disssipation_Rate*Water_In_CIS_System	OUTFLOW PRIORITY: 1	m ³ /min	Rate of water dissipation to groundwater.	UNIFLOW
	Capacity_CIS	Pipes+Storage_Tank		m ³	Sum of pipes and storage capacity.	
	Correlation_Time	1		Years	Time correlation parameter for pink noise generation.	
	Depth	15		m	Overall depth parameter.	
	Diameter	0.20		m	Pipe diameter in meters.	
	Disssipation_Rate	0.000593		Dimensionless / min	Rate at which water leaks out of CIS to groundwater.	
	Effect_of_RI_Presets	GRAPH(RI_Presets) Points: (0.000, 0), (1.000, 0.00007159), (2.000, 0.00017522), (3.000, 0.000278845), (4.000, 0.000196), (5.000, 0.00056), (6.000, 0.0022)		m/min	Scaling multiplier based on chosen Rainfall Intensity index.	
	Effect_of_water_to_capacity	GRAPH(Ratio_water_to_capacity) Points: (0.000, 0.0000), (0.105, 0.0000), (0.210, 0.0000), (0.315, 0.0000), (0.421, 0.0000), (0.526, 0.0000), (0.631, 0.0000), (0.736, 0.0000), (0.842, 0.0000), (0.947, 0.0000), (1.052, 0.1000), (1.157, 0.2010), (1.263, 0.3140), (1.368, 0.4050), (1.473, 0.4950), (1.578, 0.5890), (1.684, 0.6890), (1.789, 0.7800), (1.894, 0.9030), (2.000, 0.9970)		Dimensionless / min	Graphical function scaling runoff behavior relative to stored water ratio.	
	Mean_Function	1		Dimensionless	Central expectation variable for noise generation.	
	Noise_Seed	7		Dimensionless	Seed to make the noise deterministic or unique.	
	Pipes	$\pi * \text{Depth} * ((\text{Diameter}/2)^2)$		m ³	Calculated volume of the CIS pipes.	
	Raifalll_Intensity	Effect_of_RI_Presets*Pink_noise		m/min	Calculates rainfall intensity based on presets and pink noise variation.	

☐	Ratio_water_to_capacity	Water_In_CIS_System/Capacity_CIS		Dimensionless	Fraction of system capacity currently filled with water.	
☐	RI_Presets	1		Dimensionless	Option selection parameter index for preset intensities for simulated storm events.	
☐	Roof_Area	123		m ²	Surface area of the roof collecting rain.	
☐	Standard_Deviation	0.1		Dimensionless	Variance measurement for white noise calculation.	
☐	Storage_Tank	4		m ³	Storage tank volume parameter.	
☐	Time_Step_Function	DT		Years	Simulation time step proxy.	
☐	Water_on_Roofs	Roof_Area*Rainfall_Intensity		m ³ /min	Rate of water gathered on roof surfaces.	
☐	White_Noise	Mean_Function+Standard_Deviation*((24*Correlation_Time/Time_Step_Function)^0.5*(RANDOM(-0.5, 0.5, Noise_Seed)))		Dimensionless	White noise generator factor.	

STORM SIMULATION INFORMATION:

Storm 1: RI Presets = 1, Time = 87
Storm 2: RI Presets = 1, Time = 192
Storm 3: RI Presets = 1, Time = 402
Storm 4: RI Presets = 2, Time = 87
Storm 5: RI Presets = 3, Time = 87
Storm 6: RI Presets = 4, Time = 108
Storm 7: RI Presets = 5, Time = 108

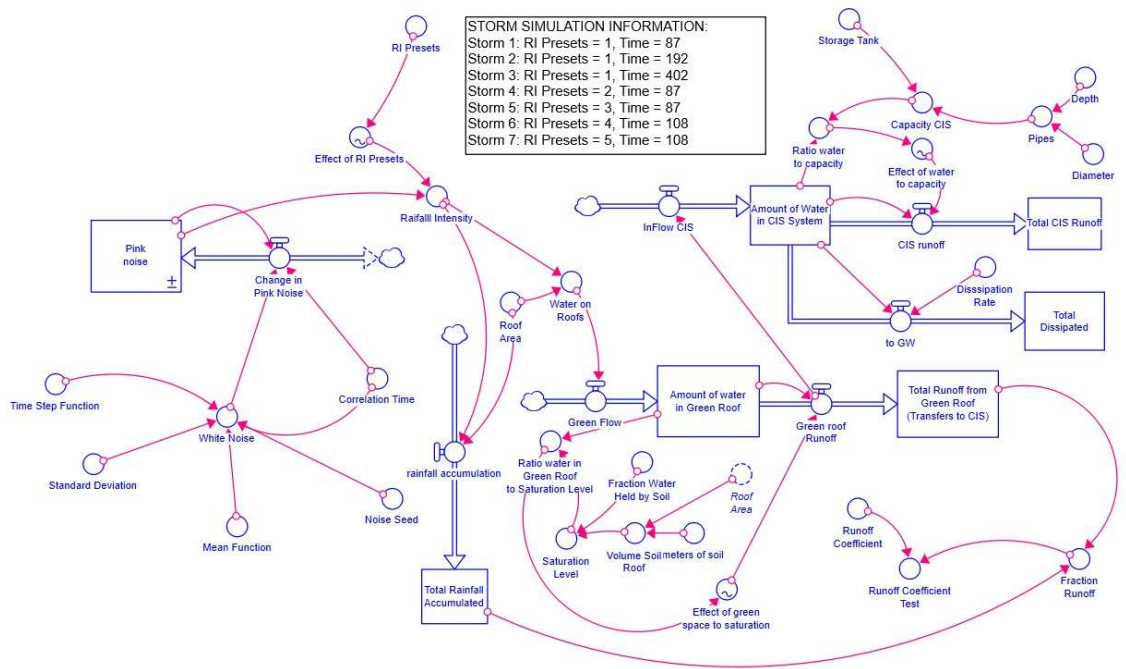
Run Spec

Start Time	0
Stop Time	87
DT	0.25
Fractional DT	False

Save Interval	0.25
Sim Duration	1.5
Time Units	Min
Pause Interval	0
Integration Method	Euler
Keep all variable results	True
Run By	Run
Calculate loop dominance information	True
Exhaustive Search Threshold	1000

8.3 Scenario 4 Model

This System Dynamics model simulates urban stormwater management by routing rainfall through a green roof system and a downstream compact infiltration system (referred to as CIS). Precipitation is modeled realistically using a pink noise generator to capture weather fluctuations. Rainwater enters the **Amount of water in Green Roof** stock, where it is stored in the soil substrate up to its **Saturation Level**. When the green roof begins to reach its absorption capacity, water overflows via **Green Space Runoff** into the **Amount of Water to CIS System** stock. This storage system safely recharges groundwater via infiltration (**to GW**), but will experience overflow (**CIS runoff**) if the water level exceeds the system's total **Capacity CIS**.



Total	Count	Including Array Elements
Variables	42	42
Stocks	7	7
Flows	7	7
Converters	28	28
Constants	13	13
Equations	22	22
Graphicals	3	3

Equation	Properties	Units	Documentation	A n n
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Top-Level Model:						o t a t i o n
☐	Amount_of_Water_in_CIS_System(t)	Amount_o_Water_to_CIS_System(t - dt) + (InFlow_CIS - to_GW - CIS_runoff) * dt	INIT Amount_o_Water_to_CIS_System = 0	m ³	A central stock tracking the current volume of water held within the storage tank and drainage pipe network of the compact infiltration system.	N O N - N E G A T I V E
☐	Amount_of_water_in_Green_Roof(t)	Amount_of_water_in_Green_Roof(t - dt) + (Green_Flow - Green_Space_Runoff) * dt	INIT Amount_of_water_in_Green_Roof = 0	m ³	A key stock variable representing the cumulative volume of rainwater currently retained within the green roof substrate. This stock rises with inflow from roof runoff and is depleted as water drains out via green roof runoff.	N O N - N E G A T I V E
☐	Pink_noise(t)	Pink_noise(t - dt) + (Change_in_Pink_Noise) * dt	INIT Pink_noise = Mean_Function	Dimen sionles s	A stock representing a temporally correlated random noise signal used to simulate realistic fluctuations in rainfall intensity. It integrates random white noise changes over a specified correlation time.	
☐	Total_CIS_Runoff(t)	Total_CIS_Runoff(t - dt) + (CIS_runoff) * dt	INIT Total_CIS_Runoff = 0	m ³	A stock tracking the cumulative volume of excess runoff that overflowed from the compact infiltration system.	N O N - N E G A T I V E
☐	Total_Dissipated(t)	Total_Dissipated(t - dt) + (to_GW) * dt	INIT Total_Dissipated = 0	m ³	A stock tracking the cumulative volume of water that has successfully drained out of this system and infiltrated into the groundwater table.	N O N - N E G A T I V E

	Total_Rainfall_Accumulated(t)	Total_Rainfall_Accumulated(t - dt) + (rainfall_accumulation) * dt	INIT Total_Rainfall_Accumulated = 0	m ³	A stock that tracks the cumulative volume of all rainfall that has fallen over the simulation period. It serves as a benchmark for evaluating system efficiency and calculating runoff coefficients.	NONEGATIVE
	"Total_Runoff_from_Green_Roof_(Transfers_to_CIS)"(t)	"Total_Runoff_from_Green_Roof_(Transfers_to_CIS)"(t - dt) + (Green_Space_Runoff) * dt	INIT "Total_Runoff_from_Green_Roof_(Transfers_to_CIS)" = 0	m ³	A stock tracking the total cumulative volume of water that has drained out of the green roof and successfully moved downstream into the compact infiltration system.	NONEGATIVE
	Change_in_Pink_Noise	(White_Noise-Pink_noise)/Correlation_Time		Per Minute	The rate of change applied to the pink noise stock, driving the fluctuation of the noise signal towards the white noise target over the correlation time.	
	CIS_runoff	Effect_of_water_to_capacity*Amount_o_Water_to_CIS_System	OUTFLOW PRIORITY: 2	m ³ /m in	The rate of overflow water exiting the compact infiltration system when inflow exceeds storage limits, leading to potential surface runoff.	UNFLOW
	Green_Flow	Water_on_Roofs		m ³ /m in	The incoming flow of rainwater directed into the green roof substrate, mirroring the volume of water falling onto the roof. It serves as the primary inflow to the 'Amount of water in Green Roof' stock.	UNFLOW
	Green_Space_Runoff	{IF TIME >= Time_Delay_GS THEN (1-Fraction_mitigated)*Total_Water_Leaving_GS ELSE 0} Amount_of_water_in_Green_Roof*Effect_of_green_space_to_saturation		m ³ /m in	The outflow of water leaving the green roof substrate, which acts as the source inflow to the downstream CIS system. Its rate is determined by the current soil saturation state and the capacity of the green space to hold water.	UNFLOW
	InFlow_CIS	Green_Space_Runoff		m ³ /m in	The volumetric flow rate of water transitioning from green roof runoff into the compact infiltration system.	UNFLOW

	rainfall_accumulation	Raifalll_Intensity*Roof_Area		m ³ /m in	The continuous rate of cumulative rainfall collection over the catchment area, feeding directly into the total accumulated rainfall stock.	U N I F L O W
	to_GW	Disssipation_Rate*Amount_o_Water_to_CIS_System	OUTFLOW PRIORITY: 1	m ³ /m in	The flow of water leaving the CIS storage system that successfully infiltrates into the groundwater table, driven by a constant dissipation rate.	U N I F L O W
	Capacity_CIS	Pipes+Storage_Tank		m ³	The total maximum water-holding volume of the entire CIS, calculated as the sum of storage tank and pipe capacities.	
	Correlation_Time	1		Years	The characteristic timescale over which the pink noise signal correlates with itself. This parameter determines how fast or slow weather patterns fluctuate within the simulation.	
	Depth	15		m	The physical length or depth of the drainage pipes, used alongside diameter to determine the pipes' total water volume capacity.	
	Diameter	0.20		m	The physical diameter of the drainage pipes, used to calculate pipe capacity.	
	Disssipation_Rate	0.000593		Dimensionless/min	A constant fractional rate at which water is transferred from the storage system into the surrounding soil to recharge the groundwater.	
	Effect_of_green_space_to_saturation	GRAPH(Ratio_water_in_GR_to_Saturation_Lvl) Points: (0.000, 0.0000), (0.200, 0.0200), (0.400, 0.0400), (0.600, 0.0600), (0.800, 0.0800), (1.000, 0.1200), (1.200, 0.2100), (1.400, 0.4050), (1.600, 0.5000), (1.800, 0.5000), (2.000, 0.5000)		Dimensionless/min	A graphical converter mapping the saturation ratio of the green roof to its relative discharge rate. As saturation increases, the discharge rate rises nonlinearly.	

	Effect_of_RI_Presets	GRAPH(RI_Presets) Points: (0.000, 0), (1.000, 0.00007159), (2.000, 0.00017522), (3.000, 0.000278845), (4.000, 0.000196), (5.000, 0.00056), (6.000, 0.0000782)		m/min	A lookup converter mapping preset time intervals or intensities to standard stormwater test events, scaling the simulated rainfall intensity.	
	Effect_of_water_to_capacity	GRAPH(Ratio_water_to_capacity) Points: (0.000, 0.0000), (0.105263157895, 0.0000), (0.210526315789, 0.0000), (0.315789473684, 0.0000), (0.421052631579, 0.0000), (0.526315789474, 0.0000), (0.631578947368, 0.0000), (0.736842105263, 0.0000), (0.842105263158, 0.0000), (0.947368421053, 0.0000), (1.05263157895, 0.1000), (1.15789473684, 0.2010), (1.26315789474, 0.3140), (1.36842105263, 0.4050), (1.47368421053, 0.4950), (1.57894736842, 0.5890), (1.68421052632, 0.6890), (1.78947368421, 0.7800), (1.89473684211, 0.9030), (2.000, 0.9970)		Dimensionless/min	A graphical function determining the discharge rate of the storage system based on its current fill ratio. Overflow runoff occurs rapidly once the capacity threshold is exceeded.	
	Fraction_Runoff	"Total_Runoff_from_Green_Roof (Transfers to CIS)"/"Total_Rainfall_Accumulated"		Dimensionless	The calculated ratio of cumulative green roof runoff to total accumulated rainfall, indicating how effectively the green roof mitigates stormwater runoff.	
	Fraction_Water_Held_by_Soil	0.7		Dimensionless	The percentage of the soil volume that can be occupied by water when fully saturated, determining the maximum storage capability of the green roof soil.	
	Mean_Function	1		Dimensionless	The baseline average value around which the white noise signal fluctuates, establishing the steady-state expectation of the noise process.	

○	meters_of_soil	2.2		m	The constant depth of the soil substrate installed on the green roof, which dictates its overall water storage volume.	
○	Noise_Seed	7		Dimensionless	An integer value used to initialise the pseudo-random number generator for white noise, ensuring that simulations are reproducible.	
○	Pipes	$\pi * \text{Depth} * ((\text{Diameter}/2)^2)$		m ³	The calculated volumetric capacity of the drainage pipes in the system, based on their depth and diameter dimensions.	
○	Rainfall_Intensity	{IF TIME <= 3205 OR TIME >= 1765 THEN} Effect_of_RI_Presets * Pink_noise {ELSE 0}		m/min	Represents the rate of precipitation falling onto the catchment area over time, in meters per minute. It is calculated using a pink noise generator adjusted by preset rainfall effects, helping simulate realistic and stochastic rain events.	
○	Ratio_water_in_Green_Roof_to_Saturation_Level	Amount of water in Green_Roof/Saturation_Level		Dimensionless	A dimensionless index comparing the current water volume in the green roof to its maximum saturation capacity. This ratio is crucial for determining when the green roof begins to overflow.	
○	Ratio_water_to_capacity	Amount of Water to CIS_System/Capacity_CIS		Dimensionless	The current fill level of the CIS, expressed as a ratio of stored water to the total physical capacity of the system.	
○	RI_Presets	1		Dimensionless	A control variable used to select or scale different predetermined rainfall intensity scenarios.	
○	Roof_Area	209		m ²	A constant defining the physical surface area of the building roof, set to 209 square meters. This serves as the primary catchment boundary for collecting rainwater in the model.	

○	Runoff_Coefficient	0.13		Dimensionless	A target dimensionless constant representing the expected ratio of surface runoff to total rainfall for this urban roof type.	
○	Runoff_Coefficient_Test	Fraction_Runoff/Runoff_Coefficient		Dimensionless	An evaluation index that compares the measured fraction of runoff to the expected target runoff coefficient to assess green infrastructure performance.	
○	Saturation_Level	Volume_Soil_Roof*Fraction_Water_Held_by_Soil		m ³	The maximum volume of water that the green roof soil substrate can hold. It is determined by the total physical volume of the soil on the roof and the soil's fraction water-holding capacity.	
○	Standard_Deviation	.1		Dimensionless	The variability parameter for the white noise generator, dictating the intensity and dispersion of random weather variations.	
○	Storage_Tank	4		m ³	The constant physical capacity of the main CIS tank, contributing to the overall water-holding capacity of the rainwater management system.	
○	Time_Step_Function	DT		Years	Defines the simulation time increment (DT), ensuring mathematical consistency and correct scaling of the stochastic noise equations.	
○	Volume_Soil_Roof	meters_of_soil*Roof_Area		m ³	The total physical volume of soil on the roof, calculated by multiplying the roof area by the depth of the soil layer.	

○	Water_on_Roofs	Roof_Area*Rainfall_Intensity		m ³ /m in	The volume flow rate of rainwater landing on the roof surface, calculated as the product of rainfall intensity and roof area. This flow represents the immediate water load entering the green roof system.
○	White_Noise	Mean_Function+Standard_Deviation*((24*Correlation_Time/Time_Step_Function)^0.5*(RANDOM(-0.5, 0.5, Noise_Seed)))		Dimensionless	An uncorrelated random signal generated at each time step based on a normal distribution. It serves as the driver for the pink noise stock, representing rapid, unpredictable weather shifts.

STORM SIMULATION INFORMATION:
Storm 1: RI Presets = 1, Time = 87
Storm 2: RI Presets = 1, Time = 192
Storm 3: RI Presets = 1, Time = 402
Storm 4: RI Presets = 2, Time = 87
Storm 5: RI Presets = 3, Time = 87
Storm 6: RI Presets = 4, Time = 108
Storm 7: RI Presets = 5, Time = 108

Run Specs	
Start Time	0
Stop Time	87
DT	0.25
Fractional DT	False
Save Interval	0.25
Sim Duration	1.5
Time Units	Min
Pause Interval	0

Integration Method	Euler
Keep all variable results	True
Run By	Run
Calculate loop dominance information	True
Exhaustive Search Threshold	1000