MASTER IN ADVANCED COMPUTATION FOR ARCHITECTURE AND DESIGN

MITIGATING URBAN FLOODS

Iaac Institute for advanced architecture of Catalonia

Thesis Studio

Institute for advanced architecture of Catalonia

MASTER IN ADVANCED COMPUTATION
FOR ARCHITECTURE AND DESIGN

Mitigating Urban Floods

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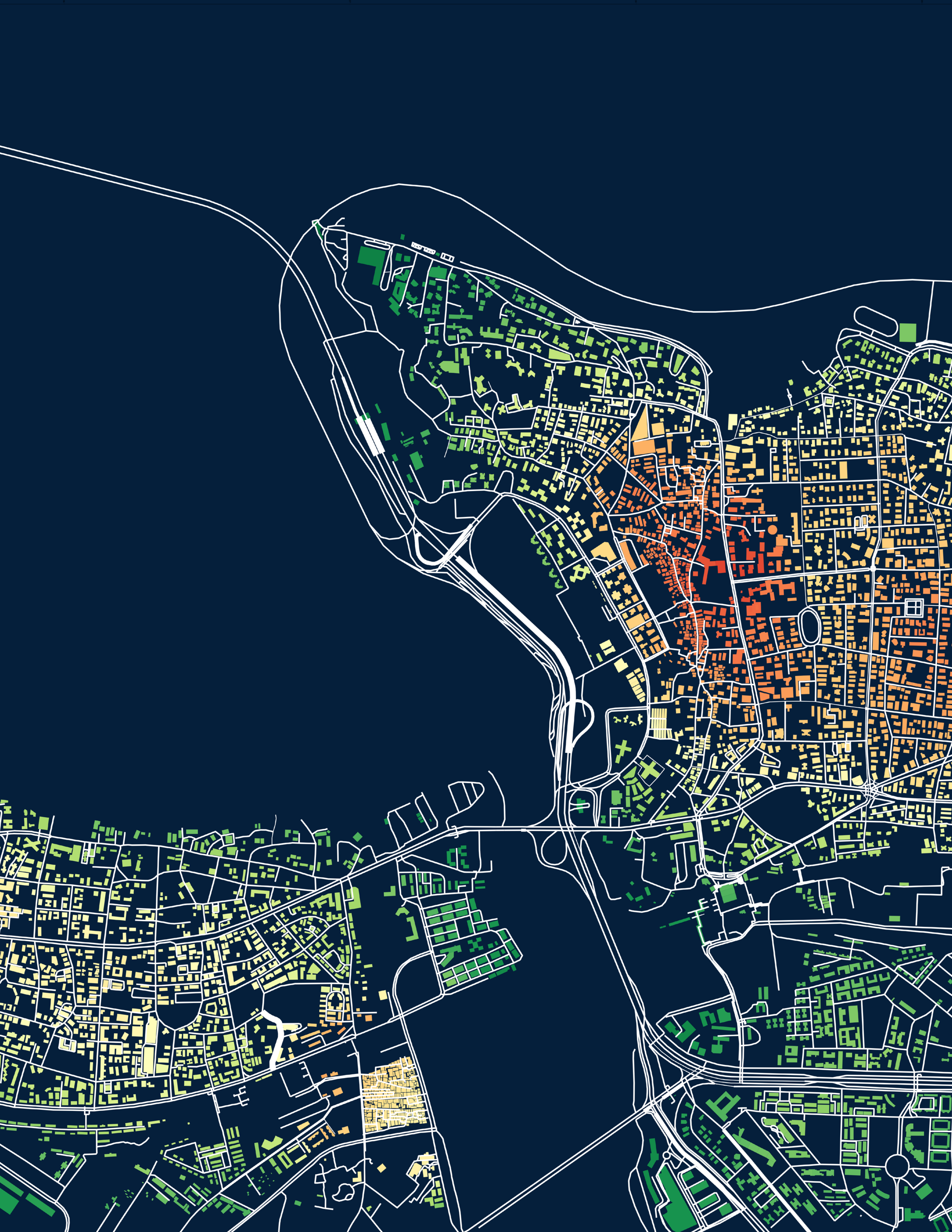
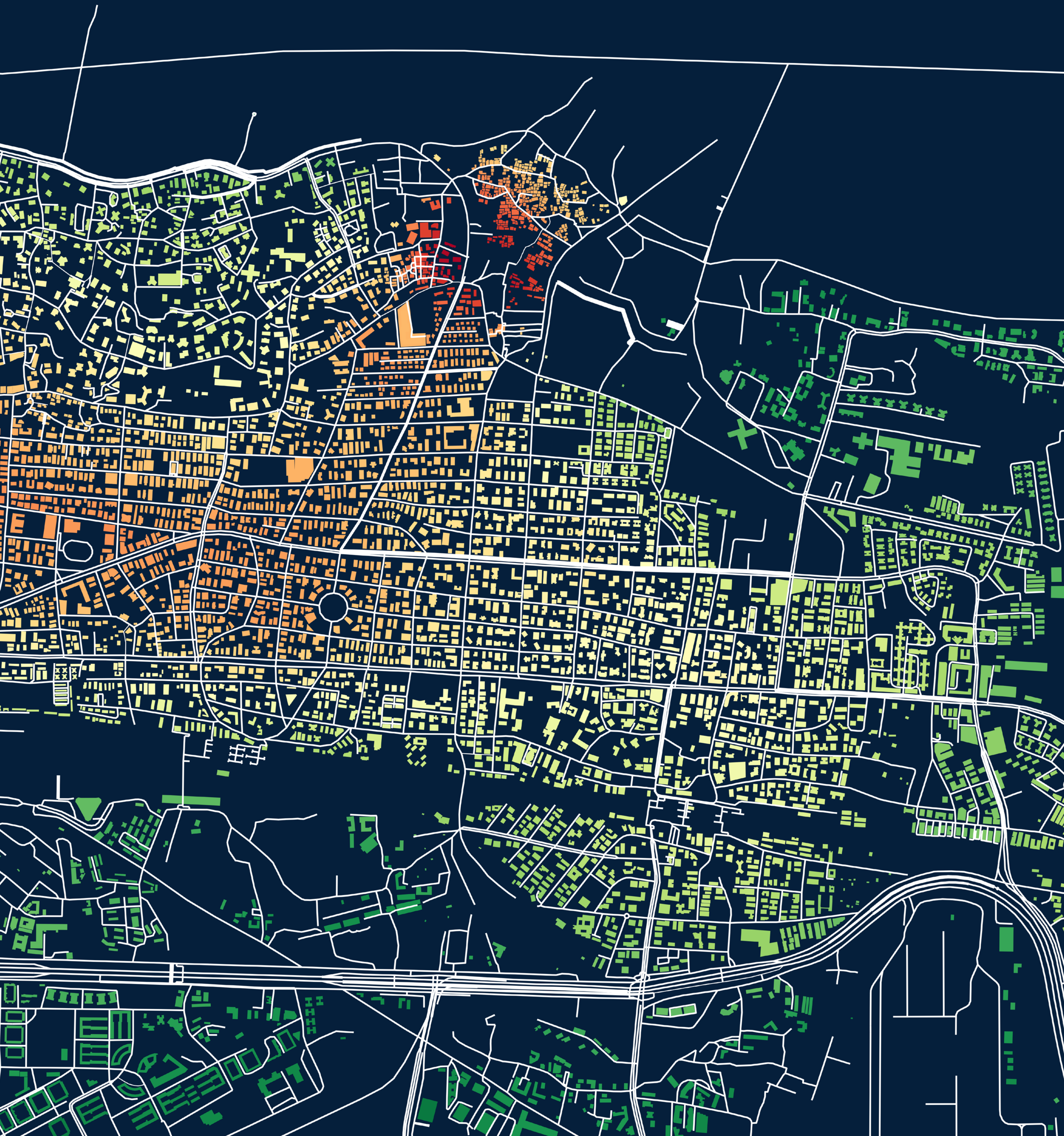
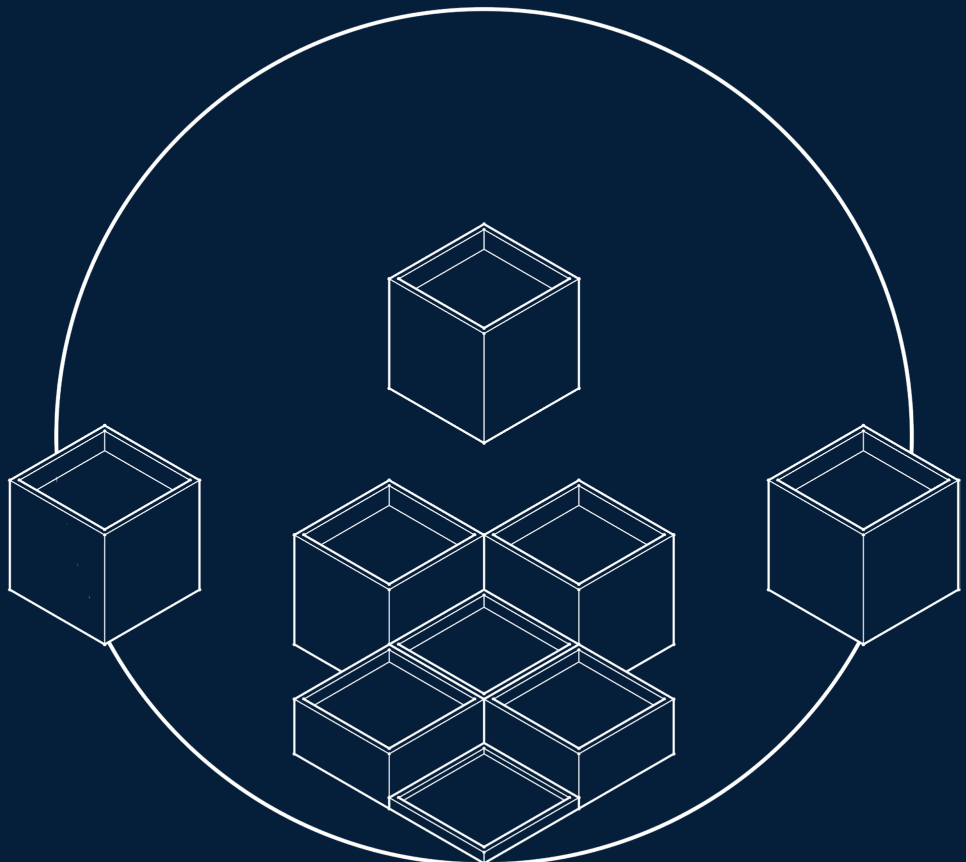




ABSTRACT

Over the past decade, hydrological disasters have consistently accounted for the largest share of all natural disasters, with floods being the most frequent. In the last century, the occurrence of these disasters has surged by up to 400%, with Asia witnessing the highest increase. India, the second most affected country in Asia, faces escalating flood risks primarily due to changes in the land use and surface degradation—factors within the realm of the designer.

This thesis investigates the role of urban design in mitigating floods, focusing on Tardeo, Mumbai, a major flooding hotspot. It aims to provide a micro-level green roof solution to improve rainwater absorption and reduce surface runoff. The research extends beyond this localized application by developing a scalable work flow using parametric and responsive modelling. Guided by rigorous performance metrics, this approach empowers designers to make informed decisions for their neighbourhoods. The project also incorporates a Human UI interface and a machine-trained model to broaden its scope, enabling wider adoption and customization of the solution for various urban settings.



CHAPTER 1
THE PROBLEM

1.1. Urban Floods

URBAN FLOODS

Analysing the escalated risks in India

Understanding Floods:

Why are they a greater problem today

From 1920 to 2020, out of total 15,406 natural disasters, hydrological disasters have been the highest accounting for 42% of them, amongst which floods have the highest percentage amounting to 34.8% as represented in Figure 01. In the last two decades the rate of increase in hydrological and meteorological is substantial in all the continents from a maximum count of 1 in 1920 to a maximum count of 800. In addition, the trend shows that the number of disasters in the Asian continent is more than the other four continents in terms or hydrological and geophysical disasters (Palanbek Yavas, Baysan, & Önal, 2022), as represented in Figure 02.

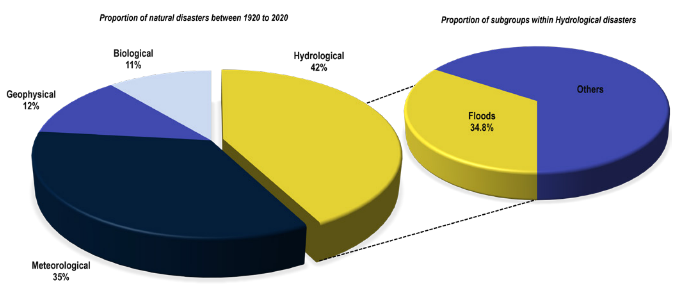


Figure 01: Pie chart representative percentage of disaster from 1920 - 2020. Made by author.

Asia's Flood Crisis:

A Critical Examination of Regional Vulnerability

As discussed earlier, the number of disasters in the Asian continent is more than the other four continents in terms of hydrological and geophysical disasters (Dutta & Herath, 2004), as represented in Figure 2. Within Asia, India is the second most affected country, and still shows a growing trend in these disasters as can be seen in Figure 3.

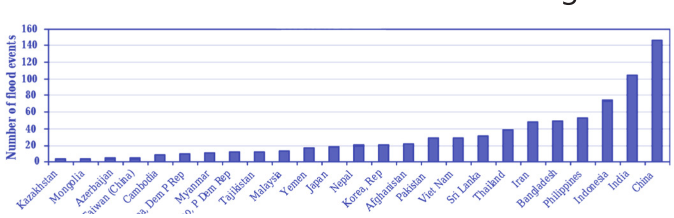


Figure 02: <No intersecting link> (Dutta & Herath, 2024)

Asia's Flood Crisis:

A Critical Examination of Regional Vulnerability

As per research, the growing trends of floods in Asia can be mainly attributed to two factors, first being climate change and the other being land use change and surface degradation. For the purpose of this research we concentrate on the second primary reason (Kanae, S., T. Oki and K. Musiake 2001).

Analysis of Urban and Rural Floods:

Assessing the Heightened Hazards in Urban Areas

In India, between 2000 and 2015, 35% of new urban development in the 10 most populous cities occurred within a 20 km radius of city centers, and much of this development was on low-lying, vegetated areas with high recharge potential. Studies indicate that for every 1% increase in impervious surface area, there is a corresponding 3.3% increase in urban flood magnitude. In these cities, built-up cover has risen by 30% to 412%. The resulting urban flooding accelerates damage due to increased density and the development of catchments. Consequently, flood peaks can rise by a factor of 1.8 to 8, and flood volumes can increase up to 6 times (Goswami & Basak, 2020).

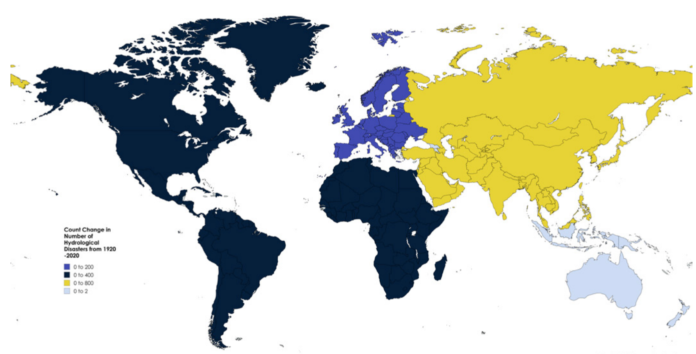


Figure 03: (Yavaş, Baysan, & Önal, 2022)

Factors Causing floods in Urban India

Meteorological Factors
Concentrated heavy rainfall

Hydrological Factors
Surface Run off >> Soil Infiltration rate due to decrease in previous surfaces.

Anthropogenic Factors
Encroachments on water bodies, obstructing natural flow of water

Outdated Grey Infrastructure
Storm water drainage lacks capacity as outdated and not up-kept.

(Zope, Eldho, & Jothiprakash, 2015)

Correlating with Mumbai's Flood Challenges

Meteorological Factors (Heavy Rainfall)
Average precipitation of 800mm/hour in Mumbai during July.

Hydrological Factors

- Loss of 40% of mangroves between 1995 to 2005..
- Increase in built-up land by +59.66% from 1995 to 2009.

Anthropogenic Factors
25% loss of water bodies due to rapid urbanization.

Outdated Grey Infrastructure
Antique drainage system capable of carrying only 25ml of water/hour.

(Sansare & Mhaske, 2020)

Flooding hotspots in Mumbai

- Malad West
- Kalanagar Junction (Bandra)
- Gandhi Market (Sion)
- Kalina
- Kurla Station
- Tilak Nagar
- Mankhurd
- Mumbai Central
- Nana Chowk
- Hindmata Parel
- Kings Circle Matunga

Figure 04: Flooding at Dahisar, The Quint, 2019

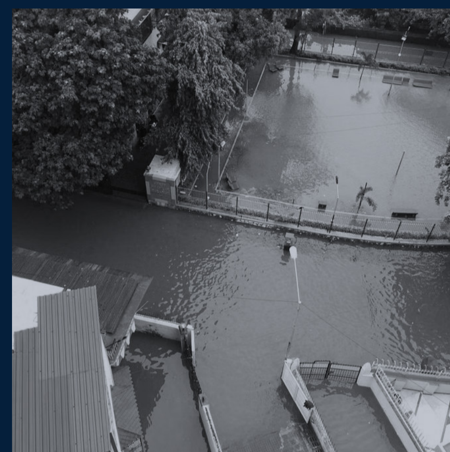


Figure 05: Postal colony in Chembur flooded The Quint, 2019)

Figure 06: Flooding Kurla Station The Quint, 2019

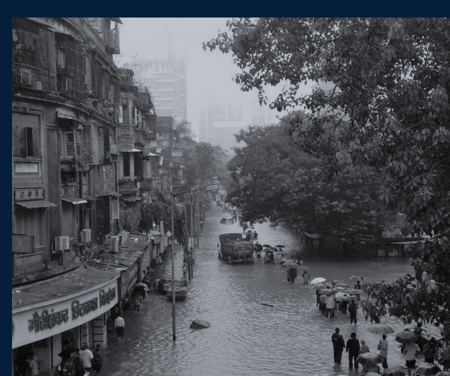
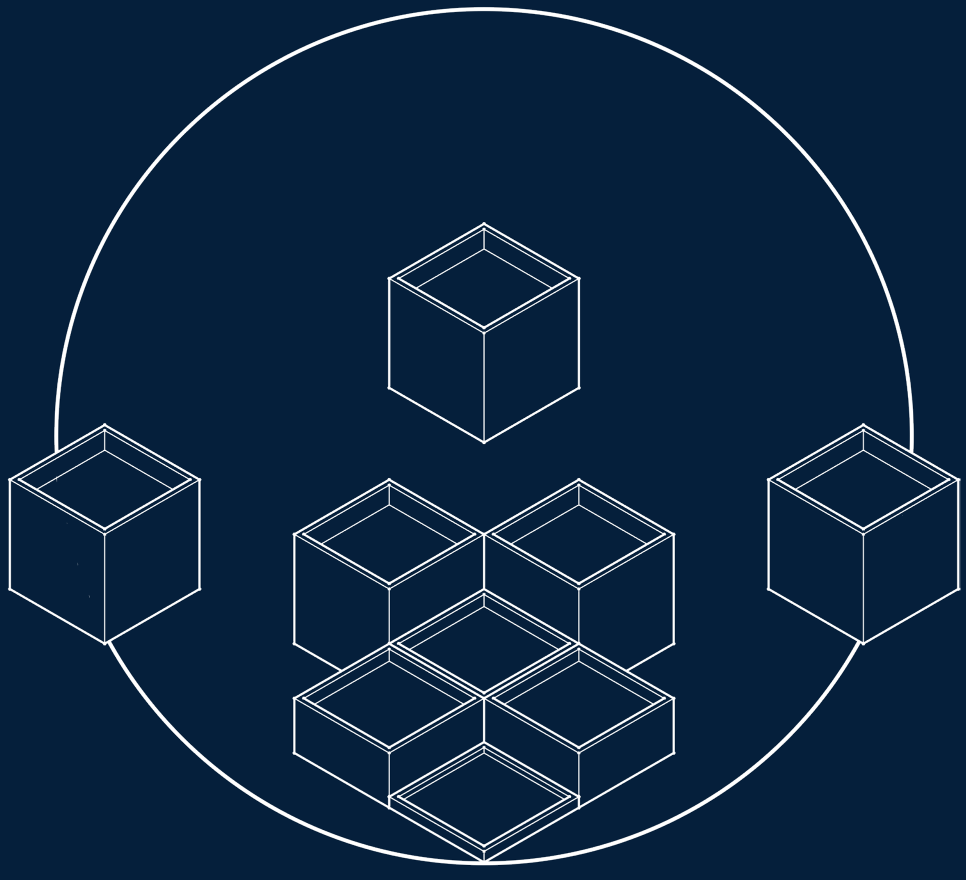


Figure 07: Flooding at Hindmata, The Quint, 2019

CHAPTER 2
RESEARCH

2.1. Goal and Objectives
2.2. Methodology
2.2. Project Precedents
2.3. Green Roof
2.4. Material and Assembly



GOAL

This research addresses the critical environmental challenges urban neighbourhoods face in rainwater management, aiming to develop a novel work flow focused on enhancing rain-water retention rather than mere harvesting but water retention to reduce surface run off to target urban floods through advanced design methods. By leveraging parametric and responsive modelling, this study will apply performance-driven metrics to guide designers in making informed, impactful decisions that address both functionality as well as sustaina-bility.

Flood Mitigation

Implement design strategies that manage and control excess rainwater during heavy rainfall, reducing the risk of urban flooding. This includes enhancing the capacity of urban landscapes to absorb and redirect water effectively.

Adaptability

Develop flexible and responsive design methods that can adjust to diverse rainfall conditions and site-specific needs, ensuring long-term resilience and sustainability in urban areas.

Reduce Rainwater Runoff

Introduce strategies that minimize surface runoff by enhancing rainwater absorption and retention through the use of green infrastructure, permeable surfaces, and innovative materials.

METHODOLOGY

INSPIRATION

Identify and outline the need for a green roof to manage storm-water runoff.

- Conduct a Literature Review on green roof technologies and their impact on storm-water management.
- Initial Site Selection for green roof case studies.
- Submission and Approval of Research Proposal.

INITIATE

- Define the Scope of the Study
- Develop a Preliminary Research Design
- Preliminary Data Collection
- Assign Roles

Assign roles, define the project's goals, and establish initial requirements.

PLAN

Develop a detailed plan for conducting the research, including methodologies for data collection and analysis.

- Detailed Research Plan
- Data Collection Plans
- Simulation and Modeling Plan

DATA COLLECTION

Implement the research plan, collect data, and perform analyses.

- Data Collection through simulation
- Analysis of Collected Data

TRANSITION

- Start setting up the user interface
- Conduct Comparative Analysis
- Develop Practical Recommendations
- Final Review and Adjustments

Finalize the research, analyze results, and prepare user interface.

CLOSE

Complete the project, present findings, and document the process. Deployment

- Final Project Review and Documentation
- Public Release and Source Code

PROJECT PRECEDENT

Large / Urban Scale

Scale and Impact:

Urban-scale projects offer insights into the broader impact of water retention solutions, especially when considering how such systems manage high volumes of runoff. These larger projects can demonstrate the effectiveness of water retention methods when applied across various infrastructures, including rooftops, streets, and open spaces.

Replication and Adaptation:

Large-scale projects often serve as models that can be adapted to similar urban environments. Precedent analysis helps identify transferable strategies that

Complex Interactions:

The interconnection between various urban elements (e.g., streets, buildings, green spaces) in large projects can provide insights into how water retention strategies need to address these complex interactions (Ashley et al., 2011).

Technological Integration:

Large-scale water retention projects often incorporate advanced technology, such as sensor networks or machine learning systems. Precedent analysis highlights the technological infrastructure needed to optimize water retention efforts (Zhang et al., 2021).

Figure 08: Sponge park photo by Xing Yi/China Daily

Policy and Regulation Guidance:

Urban-scale projects often involve collaboration with city planners, governments, and stakeholders. Understanding the regulatory environment in these contexts helps inform future projects about policy needs and possible hurdles (Jia et al., 2017).

Economic Feasibility:

Large-scale projects often include comprehensive cost-benefit analyses, offering valuable data on the financial implications and savings from reduced flooding, water conservation, and ecological benefits (Villarreal & Bengtsson, 2005).

Performance Evaluation:

Large projects often have documented assessments, allowing for the evaluation of different water retention measures and their

Studying large-scale urban projects for precedent analysis of water retention provides invaluable insights for designing efficient and sustainable storm water management systems. By examining real-world applications, performance evaluations, and innovative design strategies, we can derive practical solutions that address the complexities of urban water retention. These projects not only inspire new designs but also contribute to the development of informed policies that promote resilience in urban environments.

Sponge Cities

Location : Wuhan, China

In order to preserve the high environmental quality of this urban area and minimize disturbance from construction activities, the implementation of green roofs (Figure 3.6) emerges as a viable solution for enhancing both infiltration and retention capacities (Peng & Reilly, 2021).

Retrofitting Urban Areas

Selected streets and residential neighbourhoods were retrofitted into sponge-like areas to effectively mitigate pollution at its source. The range of sponge infrastructure employed in Wuhan's sponge city projects is extensive, encompassing rain gardens, green roofs, permeable pavements, grass swales, bio-retention facilities, depressed green spaces, previous concrete pavements, constructed wetlands, rainwater-fed wetlands, infiltration wells, infiltration basins, infiltration manholes, infiltration trenches, rainwater storage modules, previous asphalt pavements, vegetation buffer zones, wet ponds, artificial soil infiltration facilities, and ecological embankments (Peng & Reilly, 2021)

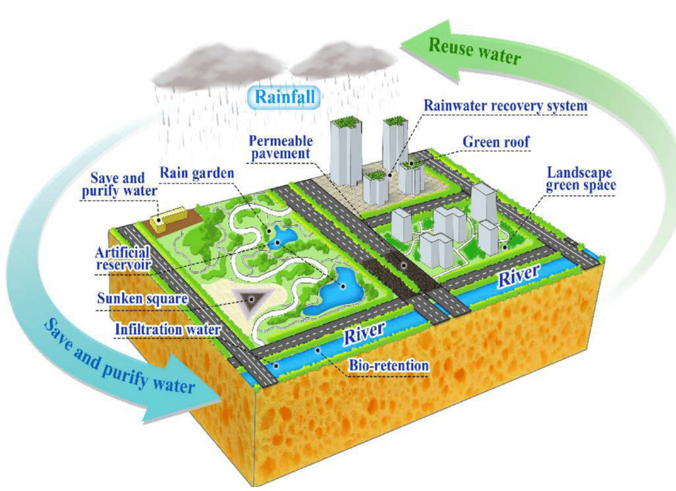


Figure 09: Sketch of the sponge city made by Shi et al., 2023

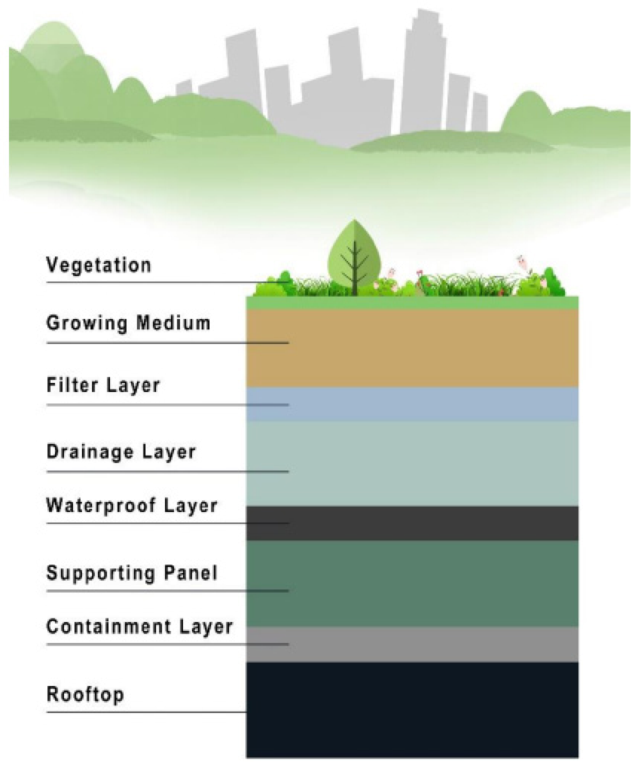
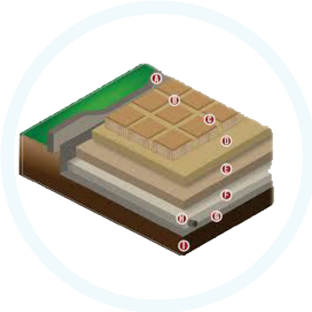


Figure 10: Green layered system Peng & Reilly, 2021

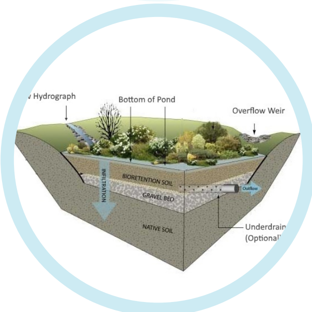
By incorporating green roofs and other sponge infrastructure, the project fosters increased urban greenery, leading to improved air quality and the reduction of the urban heat island effect. These green spaces, apart from absorbing excess rainwater, also provide habitat for local flora and fauna, promoting ecological sustainability within the city (Xu et al., 2020).

Water Management and Climate Resilience

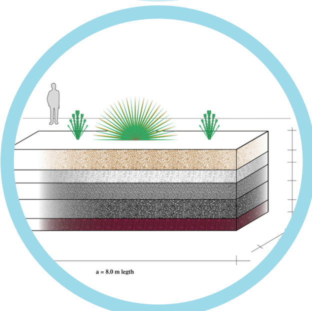
The initiative has significantly impacted the local water management system by improving the natural water cycle. The integration of these infrastructures has reduced surface runoff, promoted groundwater recharge, and enhanced water purification processes. The success of Wuhan's Sponge City initiative sets a precedent for other cities in China and worldwide to adopt sustainable urban water management practices (Zhang & Li, 2019).



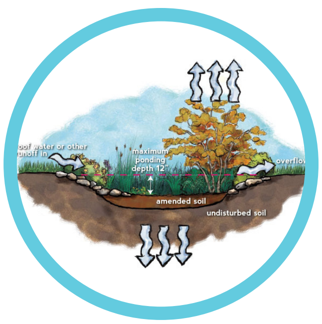
Permeable Pavements



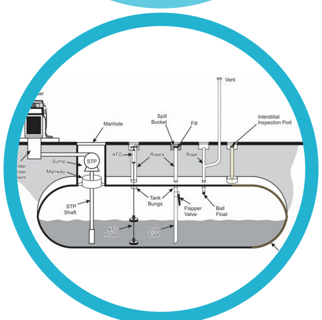
Retention Ponds



Bio-reten-tion Sys-



Rain Gardens



Underground Storage Systems

Green Roof

Cost Sq M	Resource	Manpower	Disturbance	Issue	Remarks
2,500 - 5,000	Low	Low (3-5 people)	High	• Replacement Costs • Urban Density • Maintenance	Cost varies based on materials like permeable concrete or paver's (HomeGuide) (HPD TEAM).
2,500 - 4,000	Medium	Medium (5-10 people)	High	• Space Requirements • Land Acquisition • Integration Issues	Involves excavation and lining; site conditions impact cost (JLL) (Savills).
6,000 - 9,000	Medium	High (10+ people)	Medium	• Design Compatibility • Space Constraints • High Costs	Includes plants, soil, and system setup (JLL) (CBRE India).
3,000 - 5,000	Medium	Medium (5-10 people)	Low	• Space Constraints • Retrofitting Costs • Maintenance	Plant selection and soil preparation influence cost (Sustainable Wave).
6,000 - 8,000 per m3	High	High (10+ people)	High	• Installation Disruption • High Cost • Space for Installation	Requires significant excavation and installation, especially for larger systems (ccalculator.co.in -)
2,500 - 25,000	Low High	Low (3 people) High (10+ people)	Low	• Replacement Costs • Urban Density • Maintenance	Extensive roofs are cheaper; intensive roofs with complex vegetation cost more (IndiaSpend) (The Architects Diary).

Architectual Scale

Detailed Performance Metrics:

Small-scale projects allow for a closer examination of specific design elements and their performance. Data on water retention in green roofs, such as retention capacity, evaporation rates, and drainage efficiency, can be analysed more precisely (Berndtsson, 2010).

Scalability of Solutions:

A building-level analysis provides insights into how successful water retention strategies can be scaled up or down for other building types or adapted for integration into larger urban projects (Mentens et al., 2006).

Experimental Flexibility:

Small-scale projects often provide more flexibility for experimenting with different green roof materials, substrates, and plants. These experiments can yield

Ease of Monitoring:

In small-scale projects, monitoring tools, such as sensors for water levels and plant health, can be more easily implemented and maintained. This allows

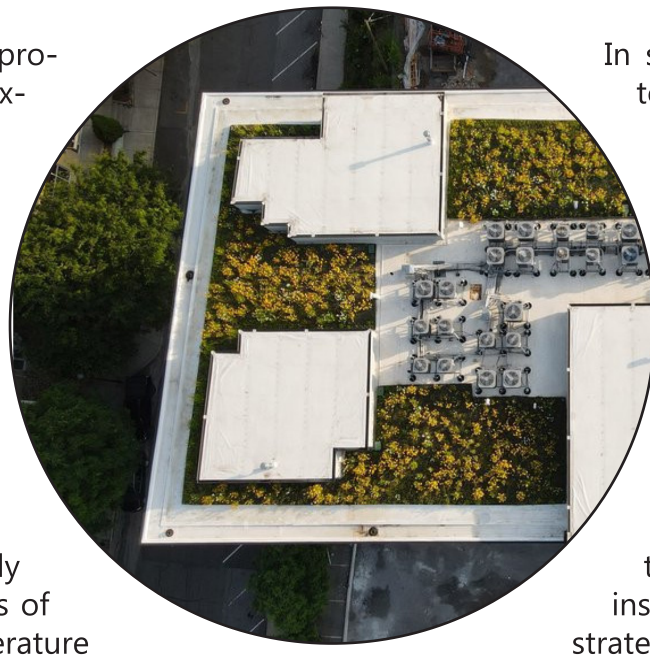


Figure 11: Aerial vie of 145 Biltmore, ilustration from greenroofs.org

Micro-climatic Impact:

Analysing smaller projects allows for a focused study on the micro-climatic effects of green roofs, including temperature regulation, moisture levels, and how these variables influence plant growth and water retention (Oberndorfer et al., 2007).

Cost-Efficiency Analysis:

Small-scale green roof projects can help determine the cost-effectiveness of different green roof designs. This includes evaluating initial costs, maintenance, and potential savings from improved insulation and storm water management (Getter & Rowe, 2006).

The study of both large-scale urban projects and small-scale building initiatives provides valuable insights into water retention strategies and the performance of green roofs. Large-scale projects allow for understanding broader environmental impacts, regulatory frameworks, and economic feasibility, while small-scale projects offer a detailed examination of performance metrics, experimental flexibility, and cost-efficiency. Both scales provide essential data on the adaptability and scalability of green infrastructure solutions, contributing to the development of optimized designs for water retention and sustainable urban development. By integrating insights from both scales, future projects can leverage these findings to address urban water management challenges more effectively, ensuring resilience against flooding and promoting ecological balance in cities.

145 Biltmore Ave

Project Team
Architect: MHA Works
Building General Contractor: Beverly-Grant, Inc
Roofing Contractor: Baker Roofing
Storm water Analysis: Robinson Design Engineers

The green roof, developed by Living Roofs Inc., apart from enhancing the aesthetic appeal of the building it also serves as a critical piece of storm-water management infrastructure.

The project team, including MHA Works as the architect and Robinson Design Engineers as the storm-water analysis experts, collaborated to create a system that addresses regional challenges such as reduced water quality, urban flooding, and biodiversity loss (Ancaya, 2023). The roof, designed as a wildflower meadow, significantly reduces storm-water runoff by utilizing a dual-media system that captures and retains large volumes of water. This innovative design exemplifies how green infrastructure can be integrated into urban settings to provide environmental and economic benefits.

Urban Heat Island Effect

The roof also contributes to mitigating the urban heat island effect by lowering air temperatures in one of the most heat-vulnerable areas of downtown Asheville (Beverly-Grant, Inc., 2023). This project not only showcases the potential of green roofs in managing environmental challenges but also demonstrates their role in enhancing urban resilience.

Figure 12: Plant selection, ilustration from greenroofs.org

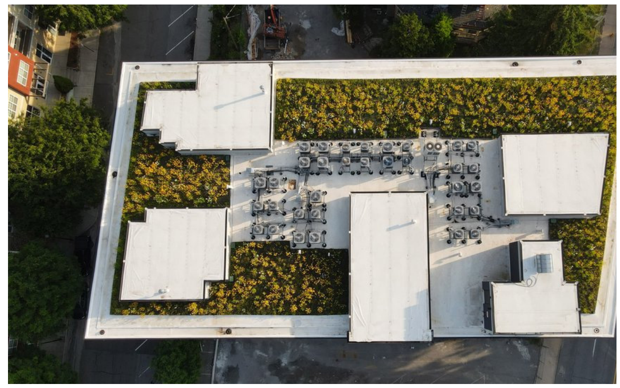


Figure 13: Aerial vie of 145 Biltmore, ilustration from greenroofs.org

Runoff Rates and Volumes

The Green roof is reducing the 2-year storm peak runoff rate by an estimated 84%. Through evapotranspiration, the vegetated roof system also prevents approximately 100,000 gallons of water from entering storm drains annually.

Storm Events

The dual-media system used on the roof has proven highly effective in managing storm-water during significant rain events. The roof retains approximately 4,200 gallons of storm-water, reducing runoff volumes for both 2-year and 10-year storm events by 76% and 53%, respectively. Furthermore, the system delays the release of storm-water, reducing the peak runoff rate by 84% for 2-year storms and 53% for 10-year storms (Robinson Design Engineers, 2023).

Sandyland Cove

Project Team
Architect: MHA Works
Building General Contractor: Beverly-Grant, Inc
Roofing Contractor: Baker Roofing
Storm water Analysis: Robinson Design Engineers

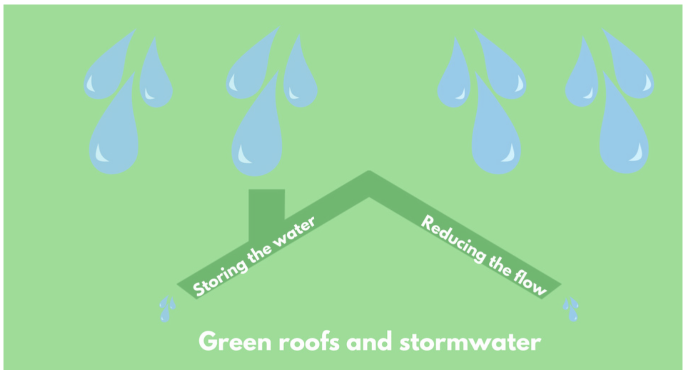


Figure 14: Diagram of the benifets of the green roof and storm water, illustration done by livingroof.org

The Sandyland Cove project in Lake Toxaway, North Carolina, exemplifies how green roof design can harmonize modern architecture with the region's ecologically rich environment. Situated in the biodiverse habitats of western North Carolina, the green roofs installed by Living Roofs Inc. Seamlessly integrate the structures into the surrounding landscape.

Native Plant Species and Wildlife

The project, developed by Platt Management Group, includes green roofs on all major buildings—main house, guest house, and boathouse. These roofs feature plant species native to the region, supporting local wildlife such as insects and birds. By mimicking native plant communities with different layers and rooting characteristics, the green roofs foster ecological resilience and blend the built environment with nature (Ancaya, 2023). This project is a prime example of how green infrastructure can complement natural ecosystems while providing environmental and aesthetic benefits.

This multi-layered approach contributes to a thriving green roof that supports pollinators and other wildlife (Living Roofs Inc., 2023).

Storm-water Management

The project prioritizes storm-water management and biodiversity. The roofs utilize a diverse mix of warm- and cool-season grasses, perennials, and ground-covers to optimize evapotranspiration and reduce the impact of raindrops on the surface. The dense planting approach, coupled with a carefully designed irrigation system, enhances the roof's storm-water retention capacity. In addition to mitigating runoff, the green roofs also reduce the heat load on the buildings, helping to regulate indoor temperatures and decreasing the structures' contribution to the urban heat island effect (Platt Management Group, 2023).

Figure 15: Site plan of the project, from greenroofs.com

GREEN ROOF

What is it?

It is a layered system that supports plant life on top of a building -- hence the term green roof. Green roofs are an efficient means of naturally insulating, which means they reduce the energy bill for heating and cooling a building, and manage storm-water runoff. They can be installed on different types of buildings, ranging from residential housing to commercial properties, turning grey urban environments into ozonic sweet spots (Dvorak & Volder, 2010).

Figure 16: Sketch of a building with an implemented green roof, image from huertorganicocr.wixsite.com

Types of Green Roofs

The most common types of green roofs are extensive roof systems and intensive roof systems. Low-maintenance, light weight systems, often 2-6" deep's Extensive Green Roofs. They are most commonly employed for their ecological services—storm-water interception and Urban Heat Island (UHI) mitigation.

- Intensive Green Roofs: This type is a deeper soil system and can have between 12 inches or more of ideal soil for many different types of plants.
- Extensive Green Rooftops: These green rooftops are usually just an inch deep with stringy, hardy drought-tolerant vegetation that grows on underused roofs.

Key Elements

Vegetation: plants (e.g. grasses, herbs, sedums or low shrubs) that bring visual pleasure to the space and wildlife protection while improving air quality (Oberndorfer et al., 2007).

Growing Medium (Soil): A precisely balanced soil mixture supplying nutrients, water-holding capability for the plants.

Filter Layer- This layer acts to help stop the drainage system getting clogged up with soil particles.

Drainage Layer: As it removes water that is located on the roof it prevents pooling (Getter & Rowe, 2006).

Root Barrier: A protective layer that will stop the roots from going under your roof.

Waterproof membrane: A watertight sheet protecting a structure from water infiltration (Vijayaraghavan, 2016).

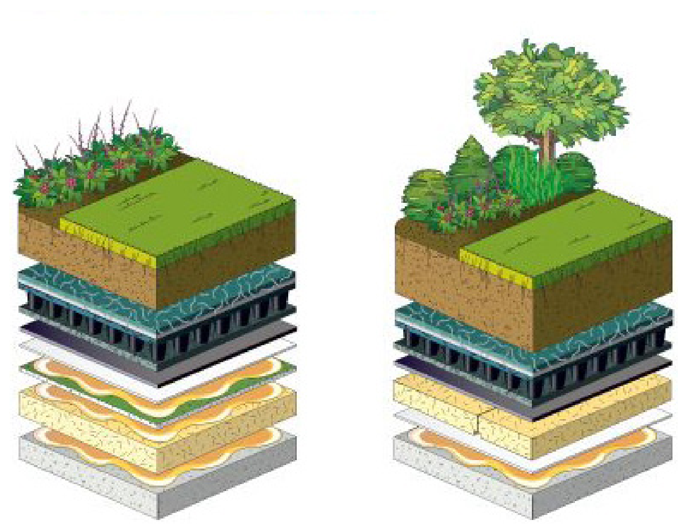


Figure 17: Green roof layer system of an intensive and extensive green, illustration from Roof Garden, Charlisle

MODULAR GREEN ROOF

Is a vegetation system comprised of pre-planted, self contained as well as easily installed replaceable and maintainable tray components established.

The system is designed to be easy to assemble since all components are integrated, requiring no assembly and allowing for easy maintenance. Cost comparison is project-dependent but approximately equal to other systems, with installation that does not require specialized expertise, though curved areas pose challenges.

This system consists of components that are pre-assembled in plastic trays, designed for easy placement on roofs.

The modular design features strategically placed holes in the center of each module, allowing excess water to drain effectively and thus prevent water-logging. These modules are designed to interlock seamlessly, ensuring a uniform and stable installation. In our application, the system will have a minimal height of 10 cm and a maximum height of 1.00 meter, accommodating various design and performance needs.

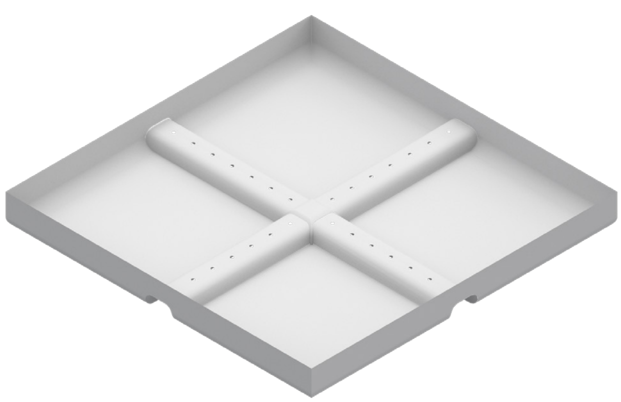


Figure 18: Render of a 1.00 x 1.00 m module with a height of 10cm, made by authors

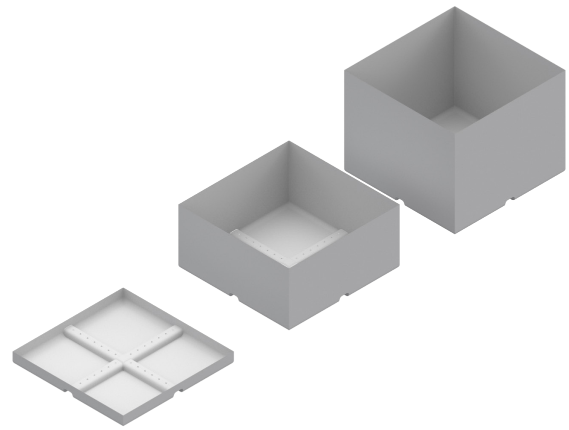


Figure 19: Different tray height, this is determine by the script. Made by authors

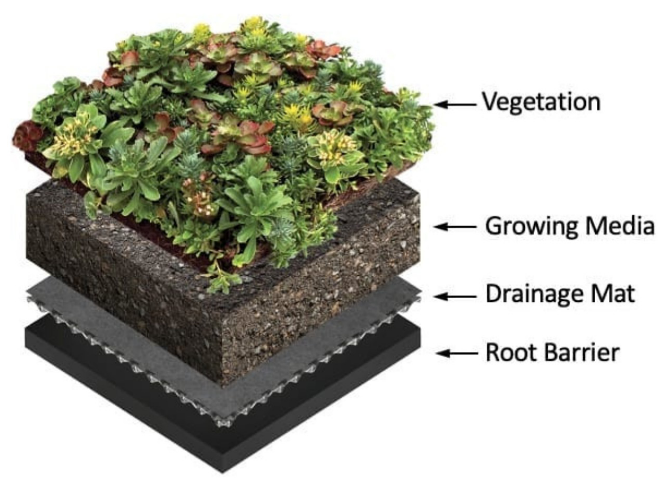
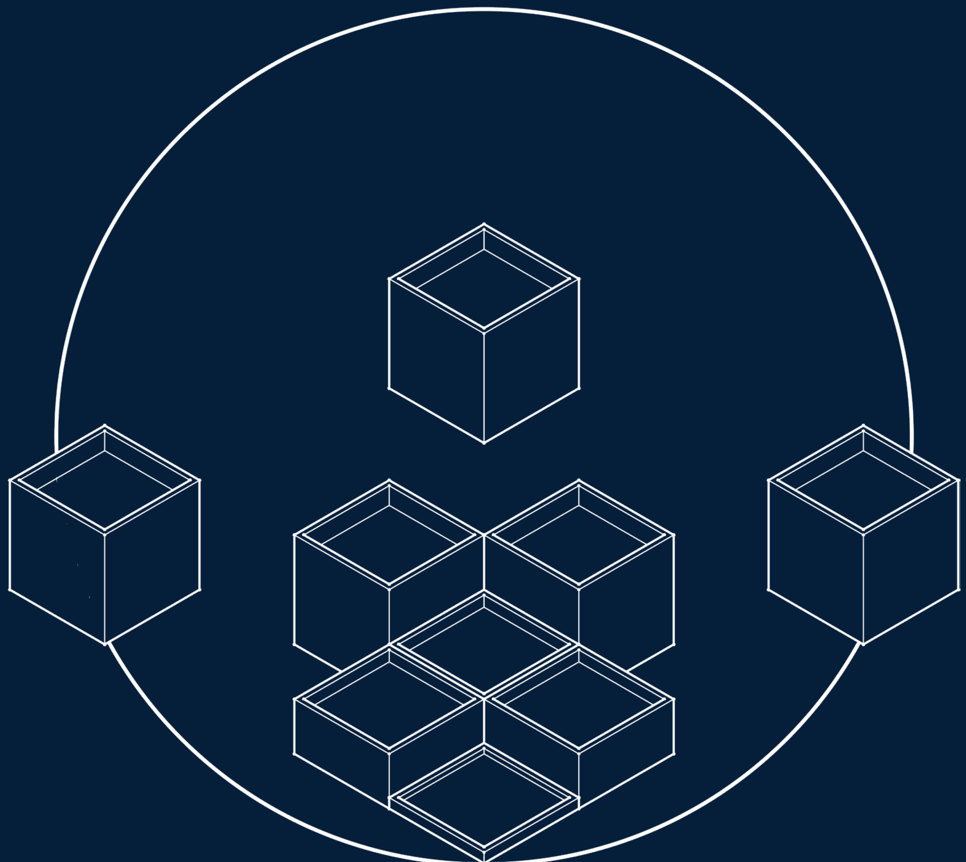


Figure 20: Green roof system that would be in the trays.



CHAPTER 3
DATA AND ANALYSIS

3.1. Flooding Hotspots
3.2. Typology Mapping
3.3. Drains roof systems
3.4. Plant Species

FLOODING HOTSPOTS

Selection of Focus Area for testing

Mapped flooding hotspots with neighbourhoods risk levels in Mumbai

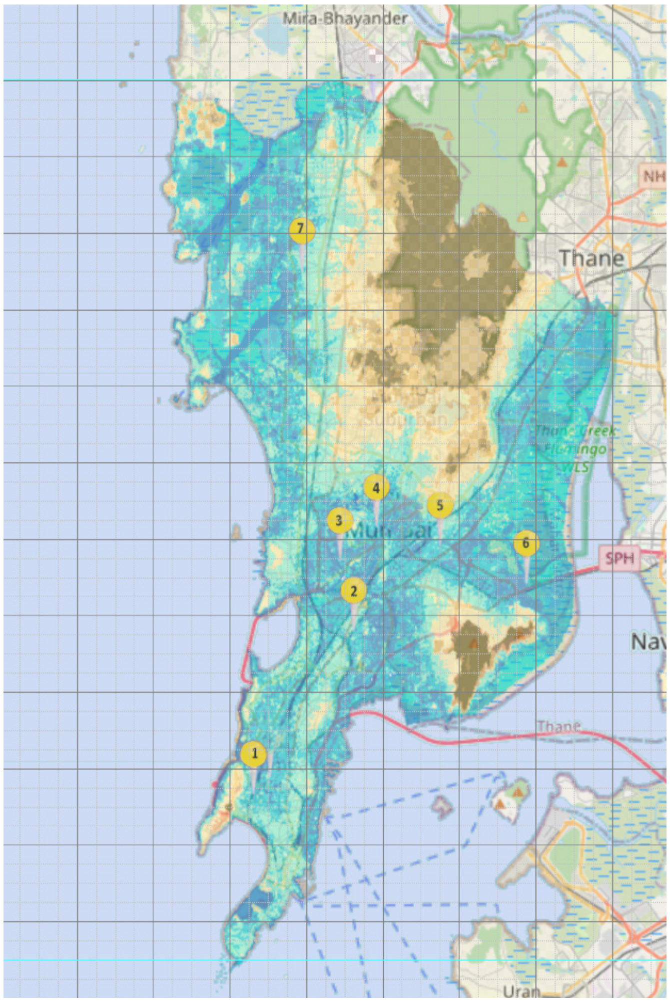


Figure 21: Flooding hotspots in Mumbai, made in Enviraj

The demarcated locations on the map are flooding hotspots mapped by an environmental consultancy, the locations taken into consideration are the ones which are OSM readable for ease of further investigation.

- Tardeo
- Kalina
- Malad West
- Sion East
- Chembur
- Bandrea West
- Mankhurd

Population density of Mumbai mapped as per census

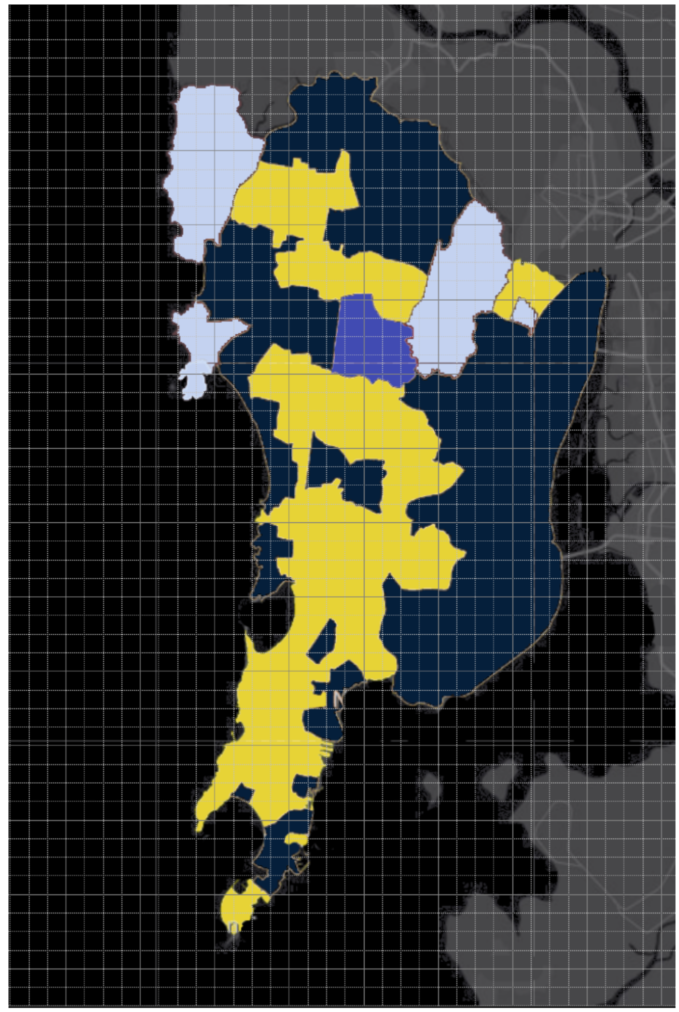


Figure 22: Population density in Mumbai, made in Arcgis

The map depicts the census data of the population density which is vital in two ways first an approximate measure of urban density and second the number of people affected with floods in these areas.

LEGEND

- Above 30,000 people/sq km
- Above 5200 people/sq km
- Above 7000 people/sq km
- 15000-3300 people/sq km

Comparing them on set urban criteria using colab

Urban criteria

In the initial analysis of flooding hotspots, a deeper investigation was conducted to identify the areas experiencing the most severe flooding. This analysis focused on regions with the highest urban density, using a set of criteria to evaluate their vulnerability:

- **Ground Built up area**

  This metric is directly proportional to the reduction of natural ground surfaces, which plays a crucial role in increasing surface runoff. As built-up areas expand, the loss of permeable ground reduces water infiltration, thereby increasing the risk of flooding.

- **Total Built up area**

  This measure reflects the overall population density of an area and indicates the burden placed on existing grey infrastructure, such as drainage systems. Higher built-up areas often correlate with higher population densities, which exacerbate stress on infrastructure during heavy rainfall.

- **Total Green Area**

  This includes all natural ground surfaces and greenfield sites, which contribute to water percolation and help mitigate surface runoff. The presence of green areas is essential for reducing flood risk, as they enhance water absorption into the ground.

- **Total Street Area**

  While this parameter is generally proportional to the ground built-up area and inversely proportional to the total green area, total street area is a critical factor in certain scenarios. For instance, in areas such as transportation hubs, parking zones, or rural-urban fringes, the relationship between streets and other variables may differ, making this parameter essential for comprehensive analysis.

- **Water Surface Area**

  The total water surface area encompasses all natural water bodies within the region, which can act as reservoirs that absorb excess rainwater. Their surrounding areas are typically are also permeable.

Data Extraction

The detailed comparison of the regions was conducted using GeoPandas. Since many of these areas lack a well-defined administrative boundary on OpenStreetMap (OSM),the entire bounding box of each region was considered. For most parameters excluding the Total Built-Up Area and Total Street Area, the necessary data was directly extracted from the GeoJSON files. However, for the Total Built-Up Area, the Total Ground Built-Up Area—calculated as the sum of all multi-polygons—was multiplied by the most common building height in the region to estimate total volume. Similarly, for the Total Street Area, the total length of streets was multiplied by the width of the roads, which was derived from the number of lanes. This methodology provided a more comprehensive and representative measure of street area within each region.

Comparative percentages mapped

All percentages are mapped proportional to their neighbourhood area

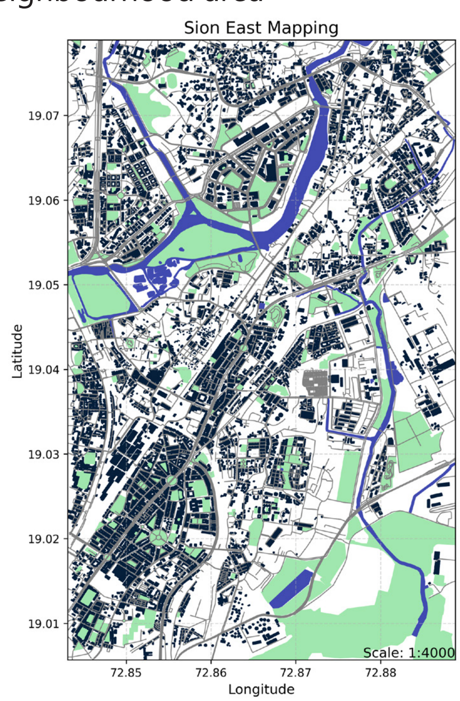


Figure 23: Sion East Map, made by authors

Ground Built Up: 12 %
Total Built Up: 84.1 %
Total Green Area: 18.6 %
Total Street Area: 28 %
Water Surface Area: 4.4 %

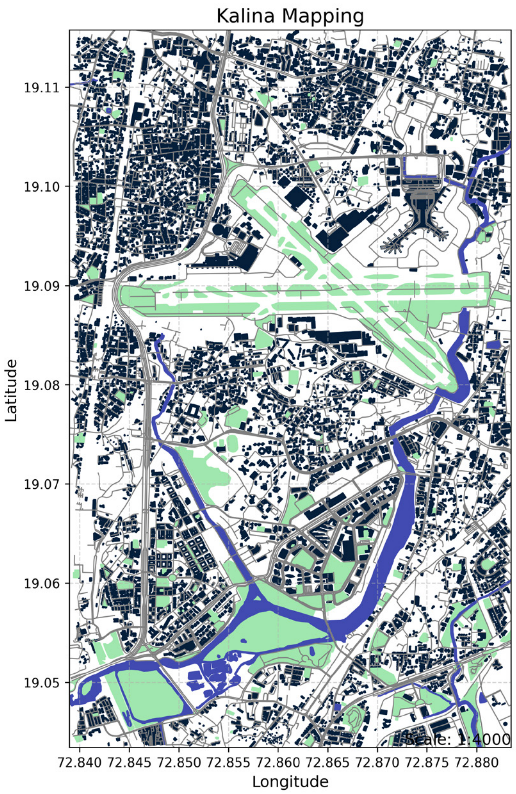


Figure 24: Kalina Map, made by authors

Ground Built Up: 12 %
Total Built Up: 84.1 %
Total Green Area: 10.2 %
Total Street Area: 21 %
Water Surface Area: 4.2 %

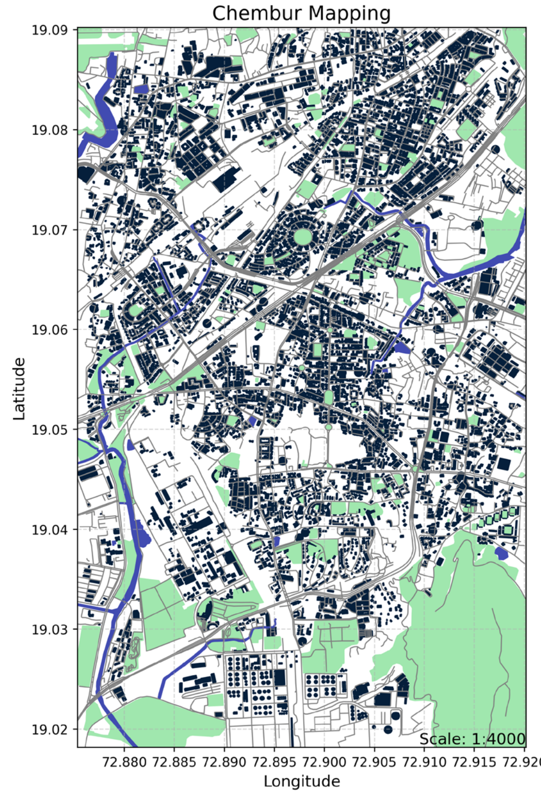


Figure 26: Chembur Map, made by authors

Ground Built Up: 10 %
Total Built Up: 32 %
Total Green Area: 73 %
Total Street Area: 10 %
Water Surface Area: 3.9 %

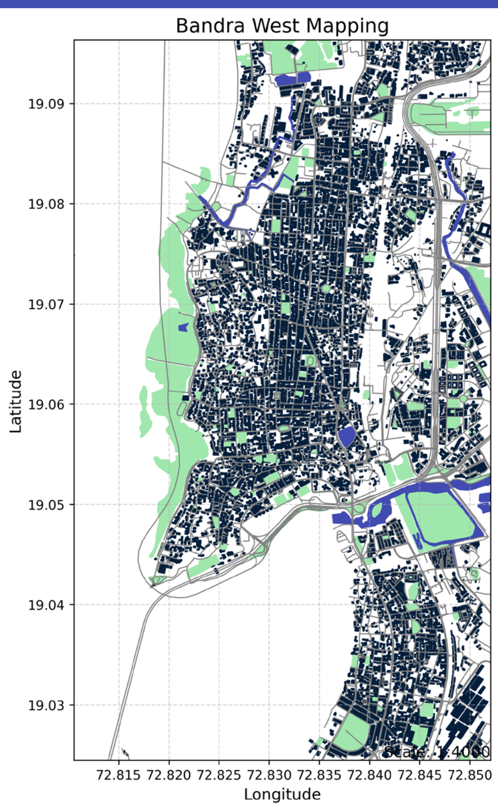


Figure 25: Bandra West map, made by authors

Ground Built Up: 8 %
Total Built Up: 88.9 %
Total Green Area: 8.3 %
Total Street Area: 18.9 %
Water Surface Area: 2.8 %

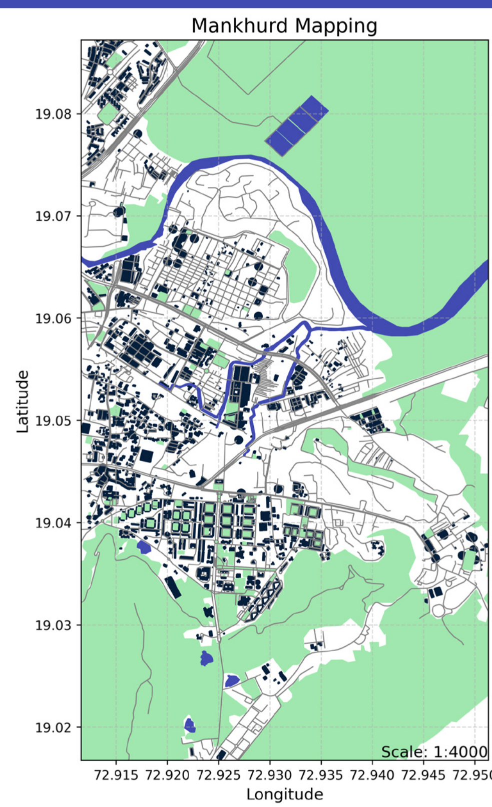


Figure 27: Mankhurd, made by authors

Ground Built Up: 2.7 %
Total Built Up: 10.8 %
Total Green Area: 50 %
Total Street Area: 4 %
Water Surface Area: 2.8 %

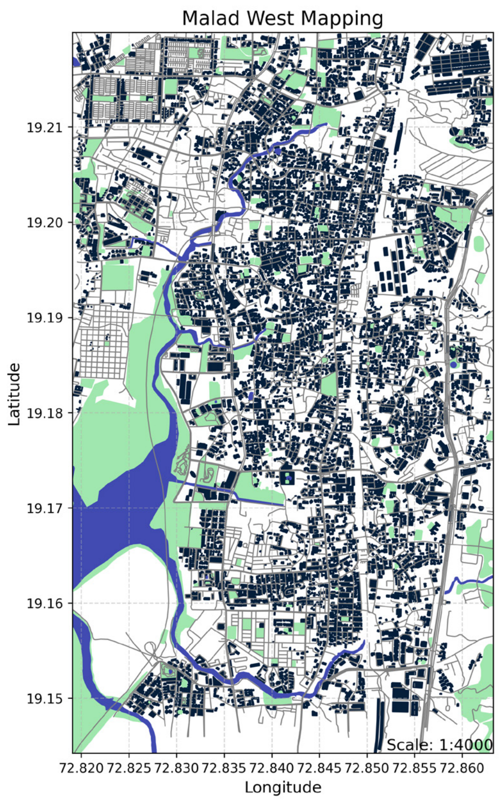


Figure 28: Malad West, made by authors

Ground Built Up: 11 %
Total Built Up: 82 %
Total Green Area: 17 %
Total Street Area: 19 %
Water Surface Area: 8.5 %

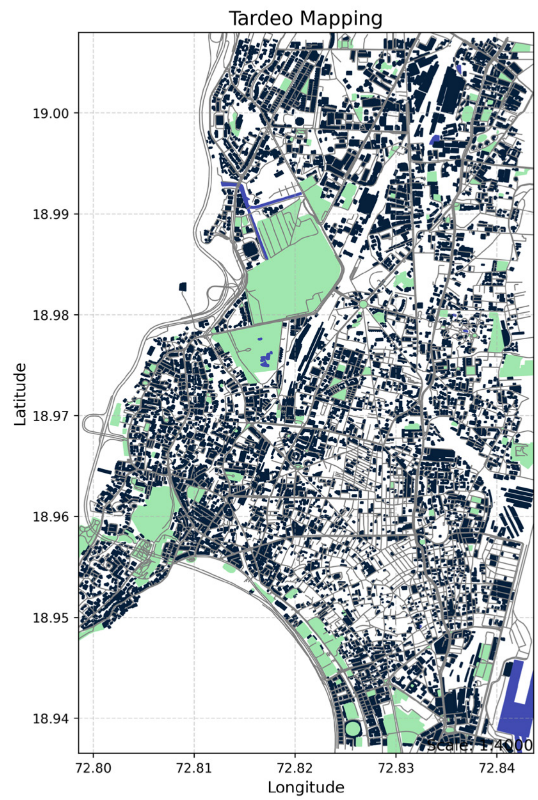


Figure 29: Tardeo map, made by authors

Ground Built Up: 12 %
Total Built Up: 126 %
Total Green Area: 7.5%
Total Street Area: 36 %
Water Surface Area: 0.8 %

Comparative Chart

As can be seen from the chart below which has been ranked from the highest to the lowest area, Tardeo ranks first in urban areas and ranks last in the natural surface areas and hence was chosen for our Micro analysis.

BUILT UP GROUND AREA	TOTAL BUILT UP AREA	TOTAL GREEN AREA	TOTAL STREET AREA	WATER SURFACE AREA
TARDEO	TARDEO	MANKHURD	TARDEO	MALAD WEST
KALINA	BANDRA WEST	CHEMBUR	SION EAST	SION WEST
SION EAST	KALINA	SION EAST	KALINA	KALINA
MALAD WEST	SION EAST	MALAD WEST	MALAD WEST	CHEMBUR
CHEMBUR	MALAD WEST	KALINA	BANDRA WEST	MANKHURD
BANDRA WEST	CHEMBUR	BANDRA WEST	CHEMBUR	BANDRA WEST
MANKHURD	MANKHURD	TARDEO	MANKHURD	TARDEO

TYPOLOGY MAPPING

Roof Type

FLAT ROOF

SLOPPED ROOF

Building Height

LOW BUILDING (1 - 3)

MID BUILDING (4 - 9)

HIGH RISE (10 - 29)

SKYSCRAPER (30 +)

Materials

PAVER

CONCRETE

ASPHALT

CONCRETE

METAL ROOFING

PLANT SPECIES
Micro Level Detailing

Native Species Reference

As the plant selection for the green roof can be a highly localized solution, the research attempts to solve it at the micro level and the decision making process is detailed down below for users to adapt to their local scenarios as well.

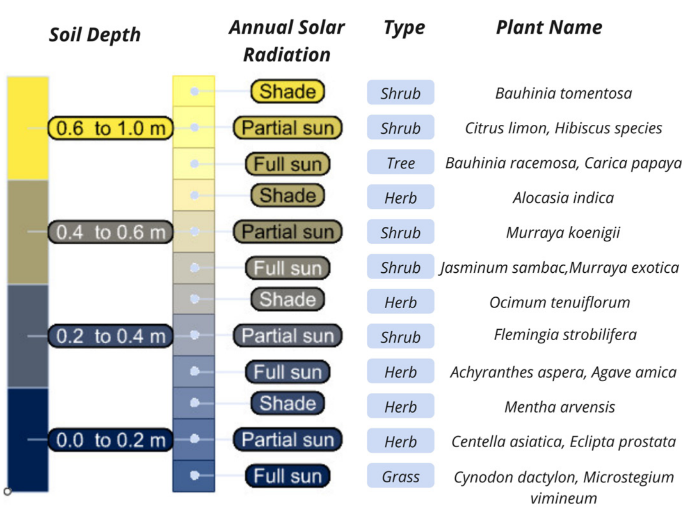
The municipal government body of Mumbai BMC for the Climate Action Plan released a citizens handbook for greening initiatives which lists out the plants which are ideal for green roof or rather terrace garden which falls under the medium scale approach.

Filtering process

The list of 85 species is filtered to exclude climbers and wetland floating species, which then are divided as per different soil depths needed which are then further filtered as per the annual radiation required, this is done so that a biodiversity is maintained and the amount of maintenance required can be minimized.

The categories for solar annual incident radiation are as follows:

Full Sun: 227.5 - 2372.5 watts per sqm
Partial Sun: 1095 - 1642.5 watts per sqm
Shade: 365 - 912.5 watts per sqm

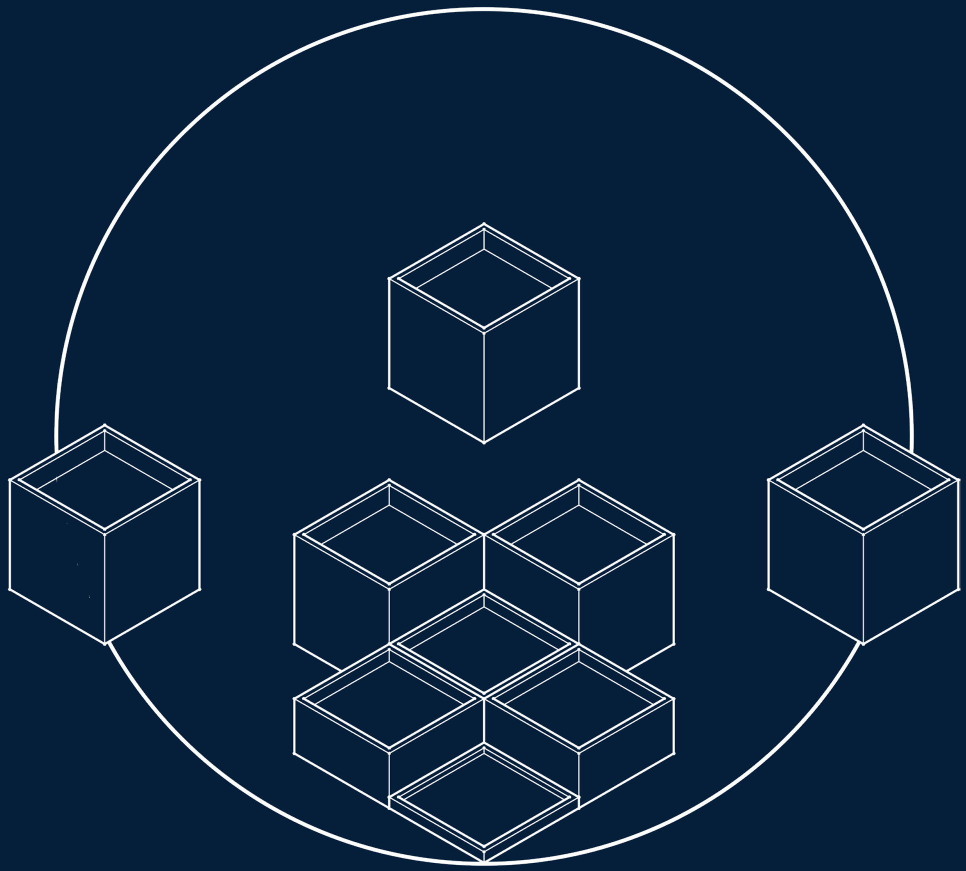


Apart from maintaining biodiversity and variation, diversifying the plant typology also aids in keeping a balance between surface runoff coefficient and the structural stability of the terrace slab. The surface runoff coefficient of the the different typology are as follows:

Grass: 0.1 to 0.35
Herbs: 0.1 to 0.30
Shrub: 0.1 to 0.30
Tree: 0.05 to 0.30

CHAPTER 4
PARAMETRIC

4.1. Stepped Roof
4.2. Radiation
4.3. Soil Depths Variation
4.4. Focus and Scale



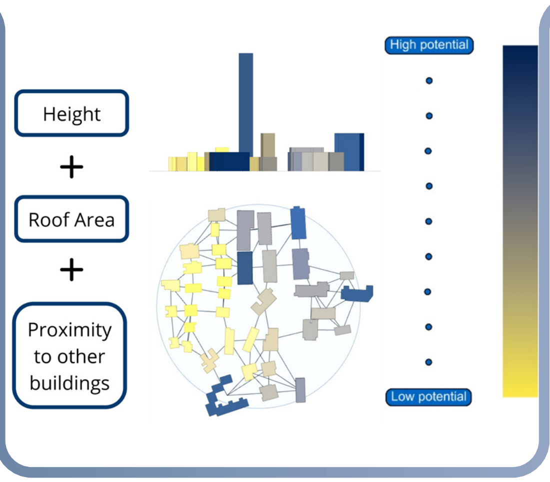
STEPPED ROOF
Computational Methodology

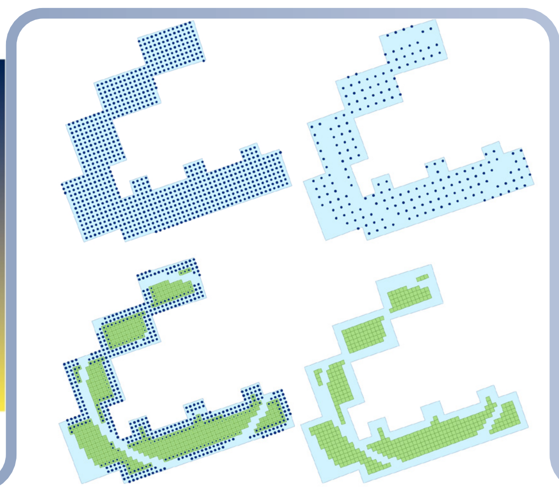
The Heights of the buildings can be set according to the list of buildings included in the selection. This is deeply explained in the Ui section later.

A Region is selected based on a point location and a circle radius that can be freely adjusted to a Region. Buildings inside the circle will be used and outside will be neglected.

Pitched roofs are to be separated from flat roofs as we are currently targeting only flat roofs, they are separated by automatically creating a layer called “pitched roof buildings” which the selected building can be assigned to.

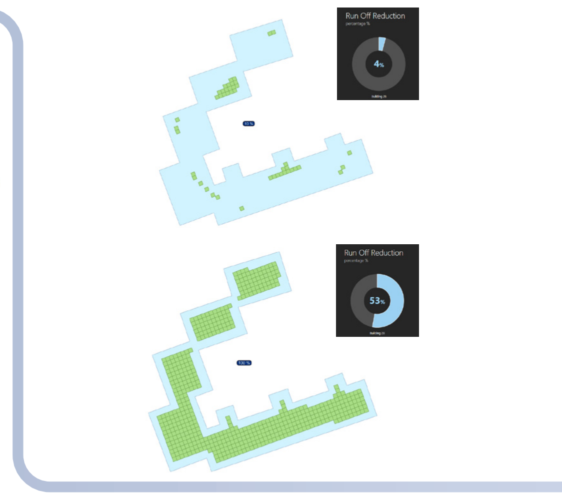
By Normalizing the Heights, Roof areas and the proximity of each building to the others, and adding the normalized values we get our ranking of these buildings. The ranking is mainly to indicate which buildings have more exposure to rainwater.





Green roof percentage adjustment. (Left)
Grid size manipulation. (Right)

Run Off Reduction readings according to percentage change.



RADIATION

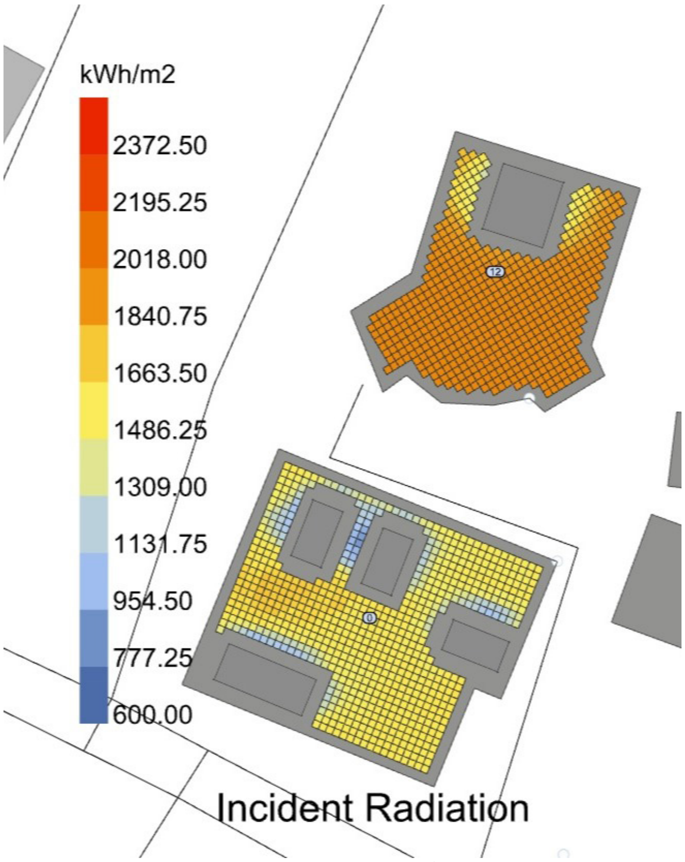


Figure 30: Incident Radiation analysis of two building. Made by authors.

By integrating Ladybug tools, we use the incident radiation on our modular green roof in order to see how is it being affected through out the whole year.

For this 3 main inputs are needed which are:

- A weather file : as we mentioned before we are targeting one of the critical spots in Mumbai which is Tardeo, so we are using generally a weather file from Mumbai, because there still not available a weather file specifically in Tardeo.
- A geometry : in this case its the surface needed to calculate the radiation for, which is the top surface of our green roof boxes.
- **A context:** as the name describes, its the geometries in the context that are needed to be taken into consideration, as the sky view is one of the parameters included in the simulation of the incident radiation. (Further description could be found at the ladybug tool documentation link:)

With the values of the incident radiation, it can be determined which regions could be vegetated with the corresponding vegetation type, in the sense of full sun, partial sun or even shade. This helps with decreasing the maintenance needed to the green roof.

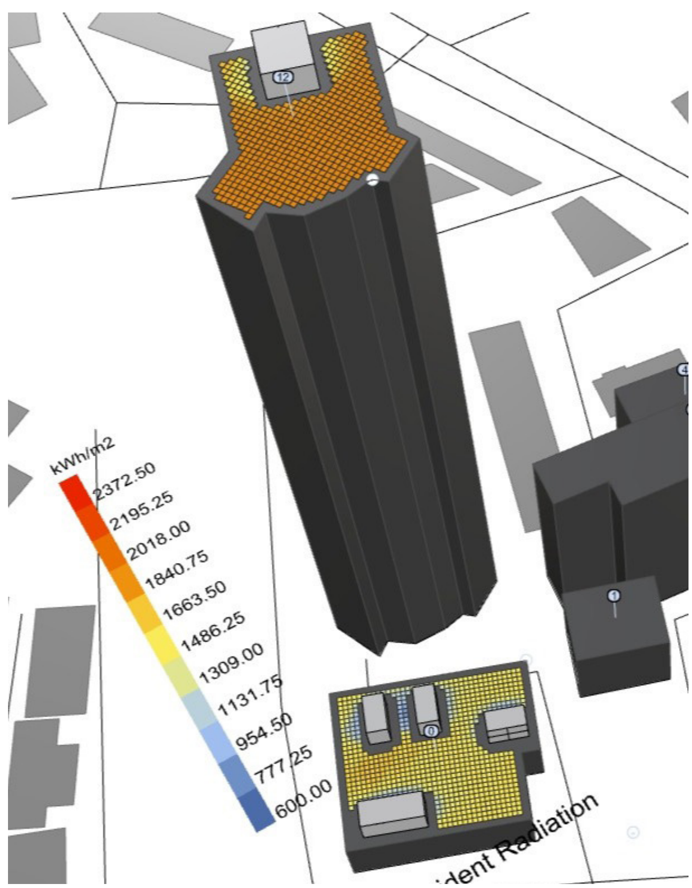


Figure 31: Incident Radiation analysis of two building. Made by authors.

SOIL DEPTH VARIATION

A soil depth variation in implemented in the stepped green roof methodology to benefit from 2 things:

- Redirection of excess run off water.
- Introduce different species of vegetation allowing bio-diversity.

As it clearly shows that the green roof modules are having higher soil depth in the middle decreasing the height towards the edges of the building or the parapet, using remapped values from the distances of each box center to the edge of the roof.

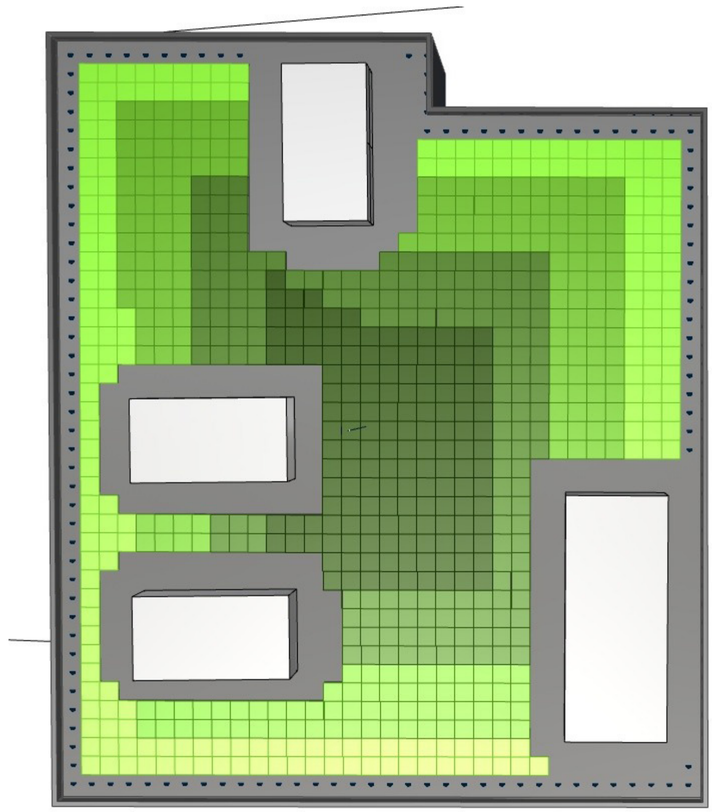


Figure 33: Plan view of the different modules. Made by authors

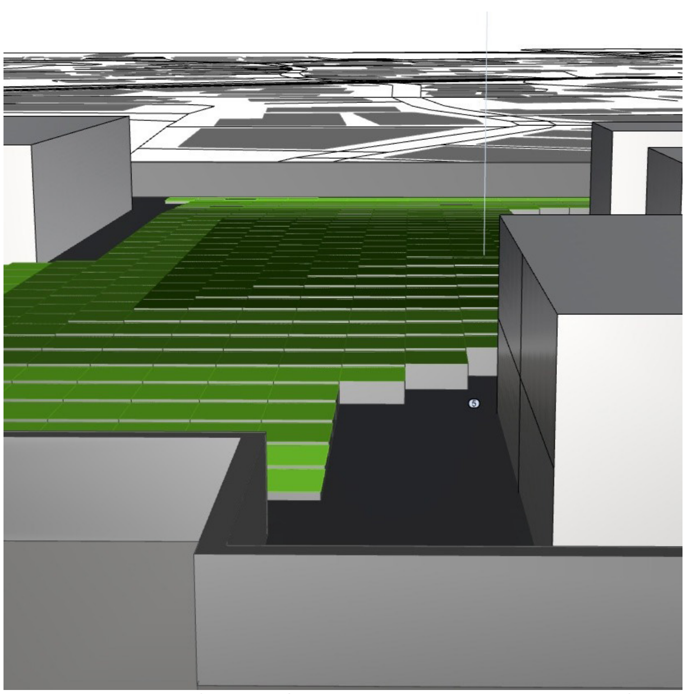
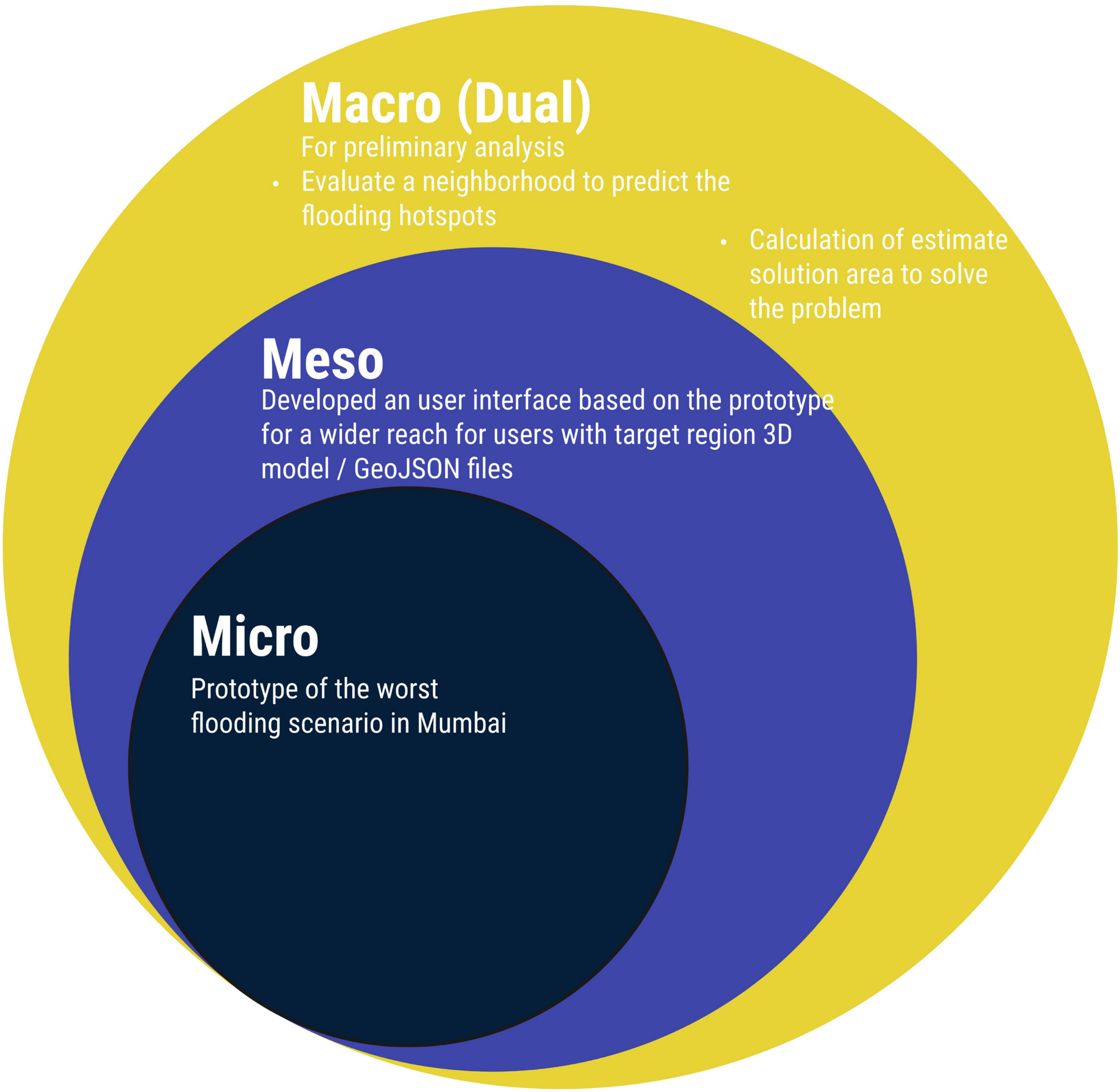


Figure 32: View of the difference height the stepped roof has. Made by authors

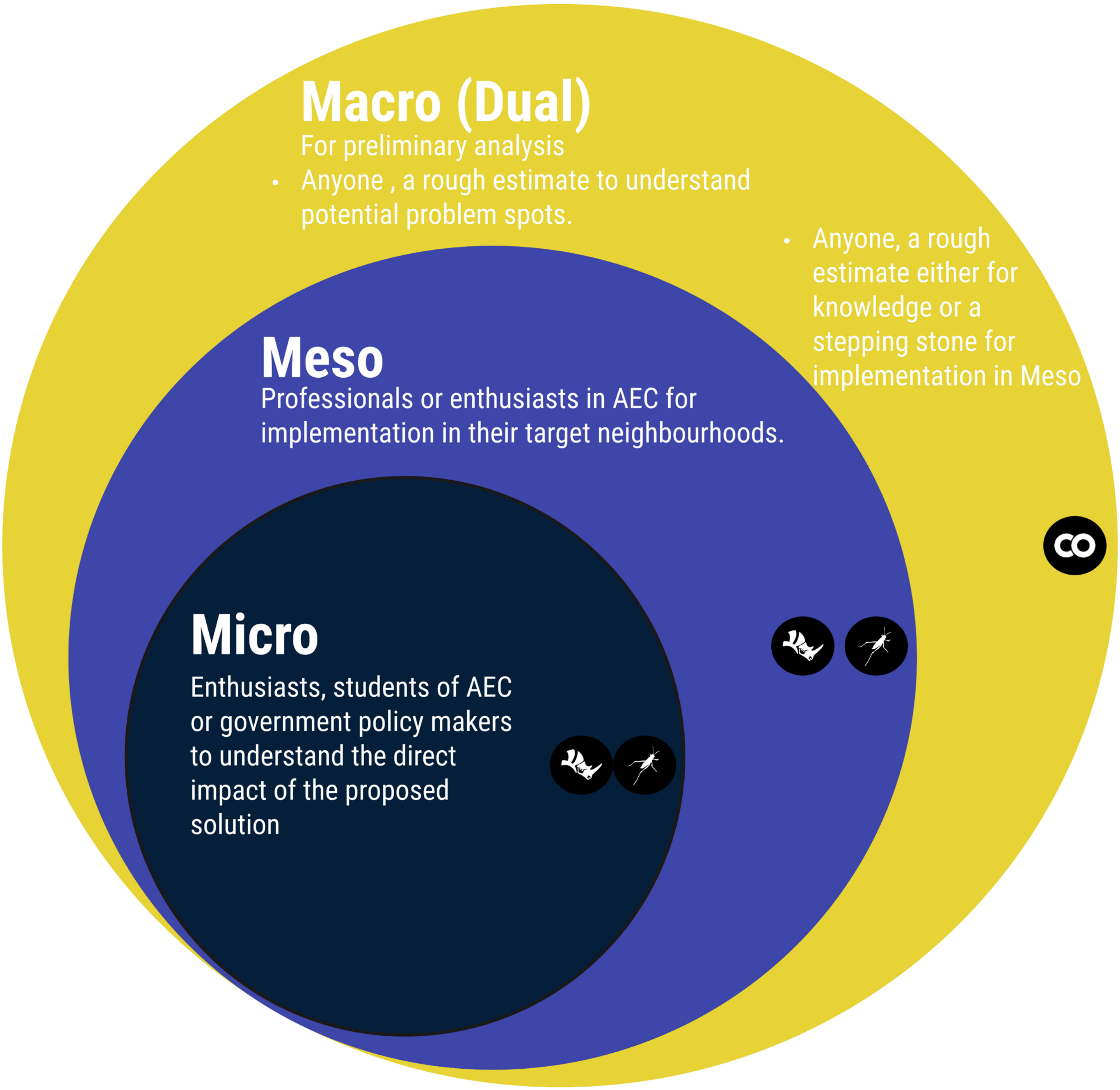
The Stepped green roof is applied with this methodology to avoid few things:

- Inconsistency throughout the heights which will lead to over shadowing on some vegetation surfaces.
- Water logging at some spots due to a drop of height in a certain cell and being surrounded by higher ones, which will result in increasing the loads in a certain point or zone on the roof.

FOCUS AND SCALE
Widening of Scope



Widening of Users



MICRO LEVEL IMPACT

Reduction of Bad Days in Tardeo

Stepped Green Roof Impact Evaluation

Context

The results till now where discussed in percentage reduction in surface runoff my changing the percentage of green roofs. To ground this research in the selected micro - context, the flooding hotspot in Tardeo that is Nana Chowk was taken as the center for the region circle of radius 500m.

Figure 34: Overral site plan of Tardeo. Illustration made by authors

Rainfall Criteria

As per the Mumbai flood preparedness guidelines published by the Mumbai municipal corporation rainfall below 64.4mm comes within the bracket of very light to moderate rainfall and is never a cause of concern, whereas the others listed below are:

- Heavy Rainfall : 64.5 - 115.5 mm
- Very Heavy Rainfall: 115.6 - 204.4 mm
- Extremely heavy rainfall: Greater or equal to 204.5 mm

Where the colors signify:

- Watch (be updated)
- Alert (be prepared)
- Warning (take action)

Rainfall Mapping

As per the historical weather data from Visual crossing a weather data tool, which takes in data from the Colaba, Mumbai weather station, monsoons in July has the heaviest rainfall, the rainfall per day were mapped for the last 2 years and color coded as per the color alerts to understand the number of bad days or rather the days which have a high probability of flooding. (Jarrett, n.d.)

Target surface runoff reduced for an impact Though there is no one exact value, a reduction in surface runoff from 20-30% can significantly improve the storm water management in flood prone areas as this helps mitigate the impact of sudden rain events .For prevention of frequent flooding 40-50% is ideal to cope with the rapid influx of water.

For the calculation for Tardeo the input values to the script or the interface where as follows:

Total region area: 31,416 sqm (500 m radius)
Total Green Area: 33234.95 sqm
Total Street Area: 201410.4 sqm

(the total street area is calculated my multiplying the total street length* most common road width in Tardeo as per the colab for extraction of data).

Figure 35 below shows that how the 7 days of extreme rainfall which would have led to flooding as the last time in flooded in 2024, Tardeo the rainfall as recorded by the nearby weather station was above 70mm, hence excluding the green color days all others cause flooding in this low lying area which is 20 out of 60 days and hence the below table shows how our solution can create such a major impact.

2023						July
SUN	MON	TUE	WED	THU	FRI	SAT
30	1 22	2 55	3 13	4 27	5 87	6 91
7 80	8 3	9 20	10 2	11 3	12 0	13 4
14 96	15 7	16 8	17 62	18 118	19 96	20 42
21 135	22 115	23 54	24 79	25 91	26 153	27 108
28 48	29 31	30 8	31 74	1	2	3

Figure 35: <No intersecting link>

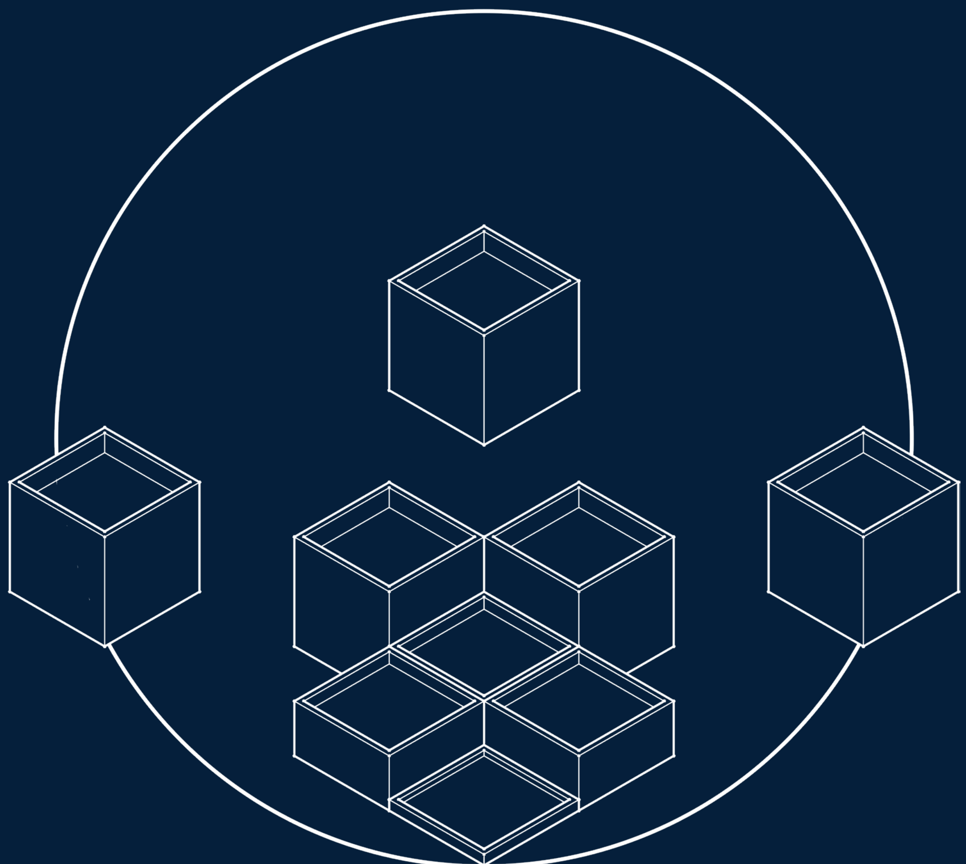
2024						July
SUN	MON	TUE	WED	THU	FRI	SAT
30	1 9	2 46	3 1.7	4 5	5 12	6 16
7 30	8 387	9 29	10 13	11 35	12 112	13 114
14 37	15 51	16 1	17 10	18 95	19 63	20 118
21 180	22 50	23 53	24 22	25 142	26 4	27 8
28 1	29 11	30 17	31 4.5	1	2	3

Figure 36: <No intersecting link>

Figure 36 its inferenced from the reference table that a minimum of 50% roof areas should have green roof to aid in mitigation of urban floods and 100% roof areas for preventing floods altogether.

Green Roof percentage	Surface Runoff Reduced
40%	17.5
50%	21.85
60%	26
70%	30.6
80%	34.9
90%	39.3
100%	43.7

Figure 37: Percentage of green roof per surface runoff. Made by authors.



CHAPTER 5
AI: MACHINE LEARNING

5.1. Model Specification
5.2. Investigation Tab

MODEL SPECIFICATION

Macro scale machine learning model

Usage of the model

The macro-scale of this thesis serves two key purposes: first, to provide an estimate of the green roof area required to meet surface run-off reduction targets without the need for a 3D model; and second, to offer an initial benchmark for further optimization in subsequent design stages. The diagram below outlines the model's inputs and outputs.

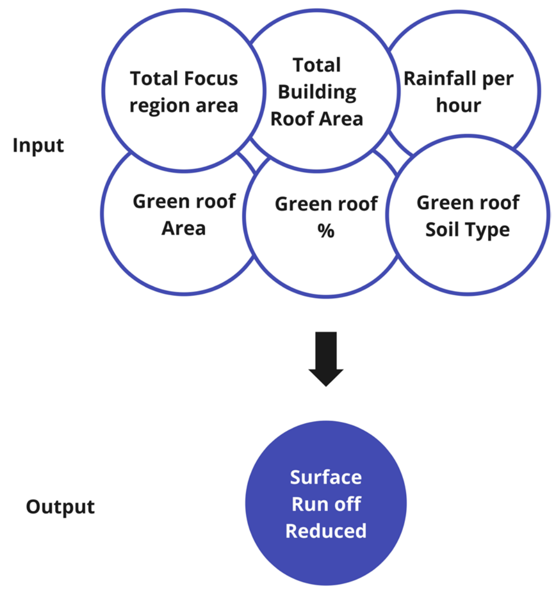


Figure 38: Diagram of inputs and output. Made by authors

Dataset Generation Process

The urban maps referenced earlier in Chapter 2 were used as base GeoJSON files for the 1,445 datasets generated. Each locality was subdivided into regions of varying sizes to capture a broad spectrum of urban densities. The wide variation in total ground surface area—ranging from 2.7% to 12%—across flood-prone localities in Mumbai made this approach ideal for dataset creation.

Description of inputs

Total Focus region area

Areas within neighborhoods which the user can focus on, for the dataset generation these points are placed randomly throughout the neighborhood with varying radii to create a fair mix, this is the starting point for other datasets inputs as all of them are relative to this area.

Total Building Roof Area

Within the bounding of the total focus region area the total area of the building geometry is calculated as taken as the total building roof area assuming them to be approximately the same.

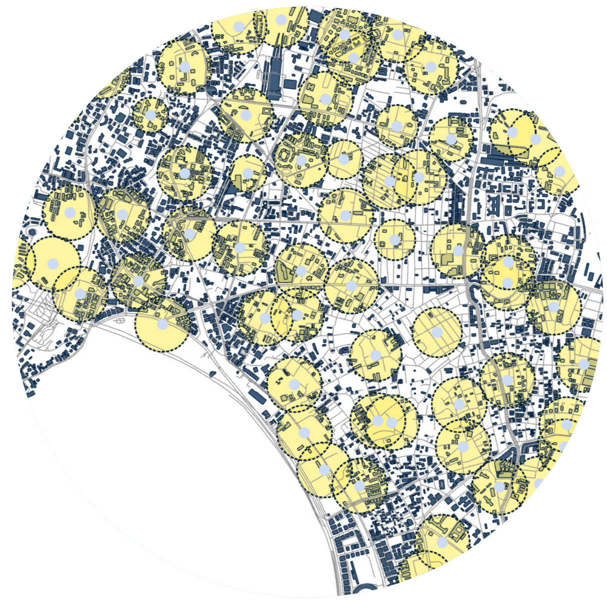


Figure 39: Data set generation spots. Made by authors

Rainfall per hour

The range of rainfall was set up from the range of moderate rainfall to heavy rainfall which as per the flood preparedness guidelines of the Mumbai Municipal corporation is from 40mm/hour to 75mm/hr.

Green roof percentage and Green roof Area

Varies the green roof area based on the varied building roof area.

Green roof Soil type

For the green roof soil type, for giving user flexibility both the extensive and intensive options are given, an essential distinction between them is that extensive greening is a simple form of greening that requires little maintenance and has few possibilities of use, whereas the intensive green roof stands for a green roof as in a garden.

The run off reduction, which in turn means increases the water retention of the soil, the saturated soil density is the parameter which is vital ranges from 1000-1450 per m cube and 1300 - 1700 per m cube.

INVESTIGATION TAB

Based on a Supervised M.L. Model

Input Data Correlation

The correlation heat-map in Figure 2 reveals that surface runoff reduction is highly correlated with the total green roof area and the percentage of green roof coverage, while showing surprisingly little dependence on maximum hourly rainfall.

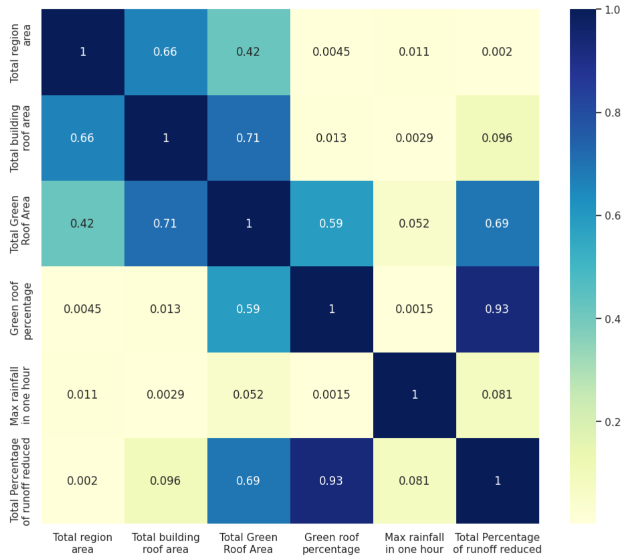


Figure 40: Correlation matrix. Made by authors

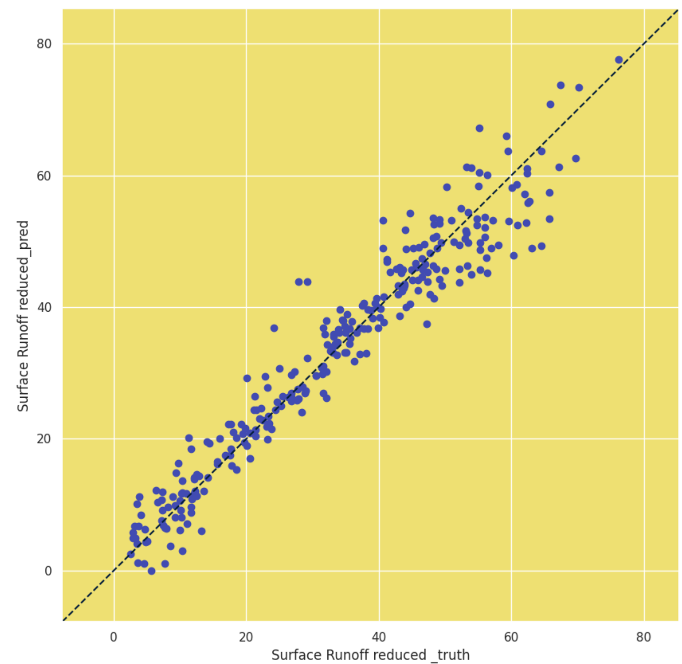


Figure 41: Linear regression, made by authors

Machine Learning Model

Linear Regression Model

From sklearn, the Linear Regression model was used as the base model, all the numerical inputs were directly standard scaled and the one categorical input was label encoded and then standard scale. The model score (R^2) was 0.936 and when the y_truth and y_predicted was plotted as can be seen in Figure 2 shows a clear diagonal trend.

XGBoost Regressor Model

The XGBoost regression model was trained on 1445 datasets which were generated on varying urban densities. The best parameters for the model which were found after a grid search are learning rate:0.2, maximum depth:3, number of estimators:300 and subsample of 0.8, the R^2 score model is 0.981 though not much greater than the linear regressor score but as seen in the predicted and truth plot, it shows a much stronger diagonal trend. Hence this model was chosen for deployment.

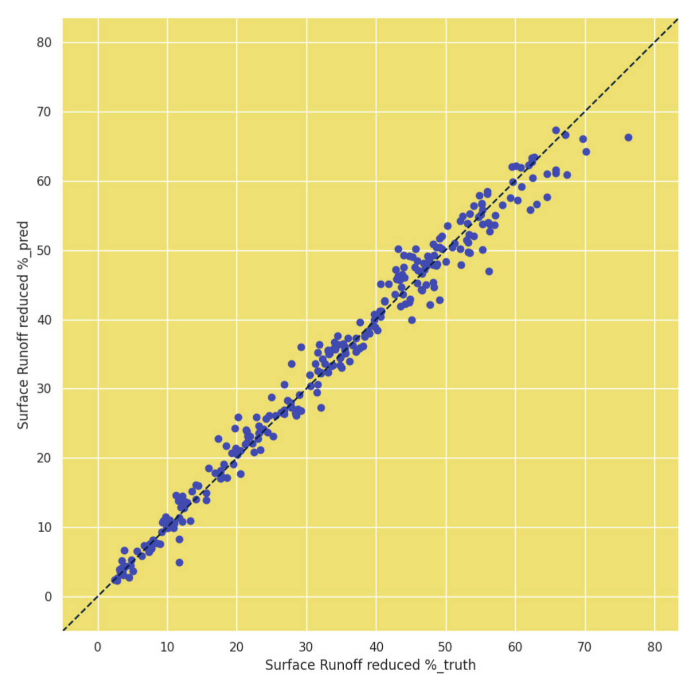
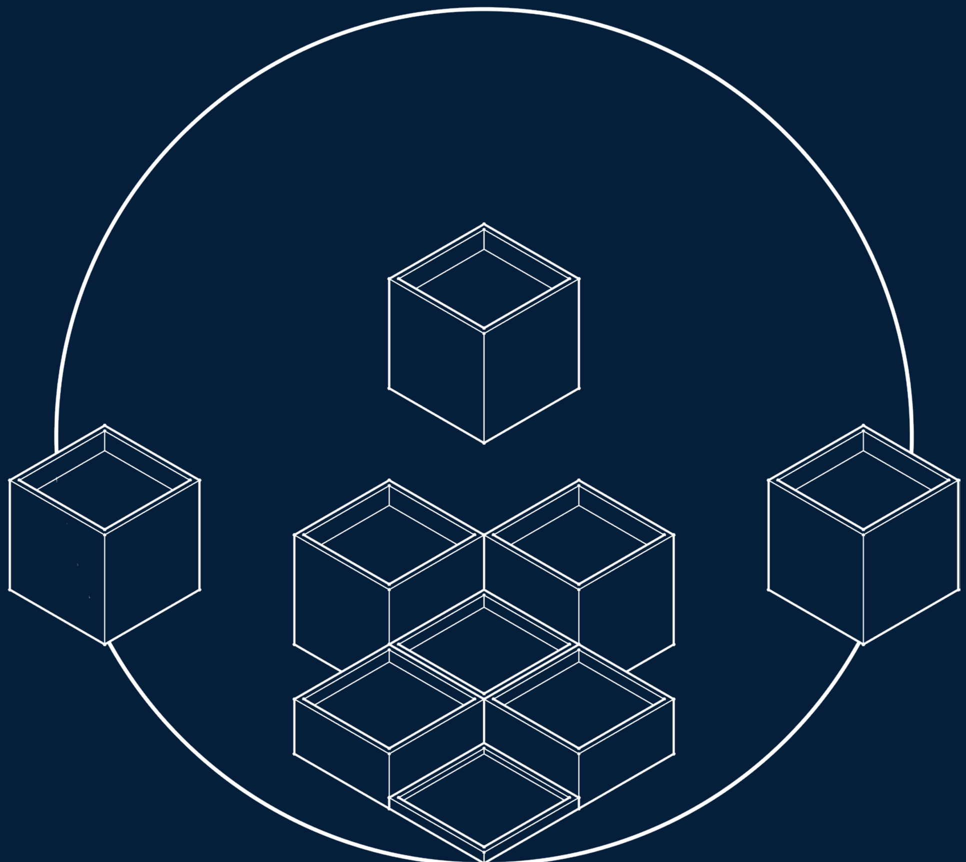


Figure 42: Linear regression (XGBoost). Made by authors

CHAPTER 5
User Interface



USER INTERFACE

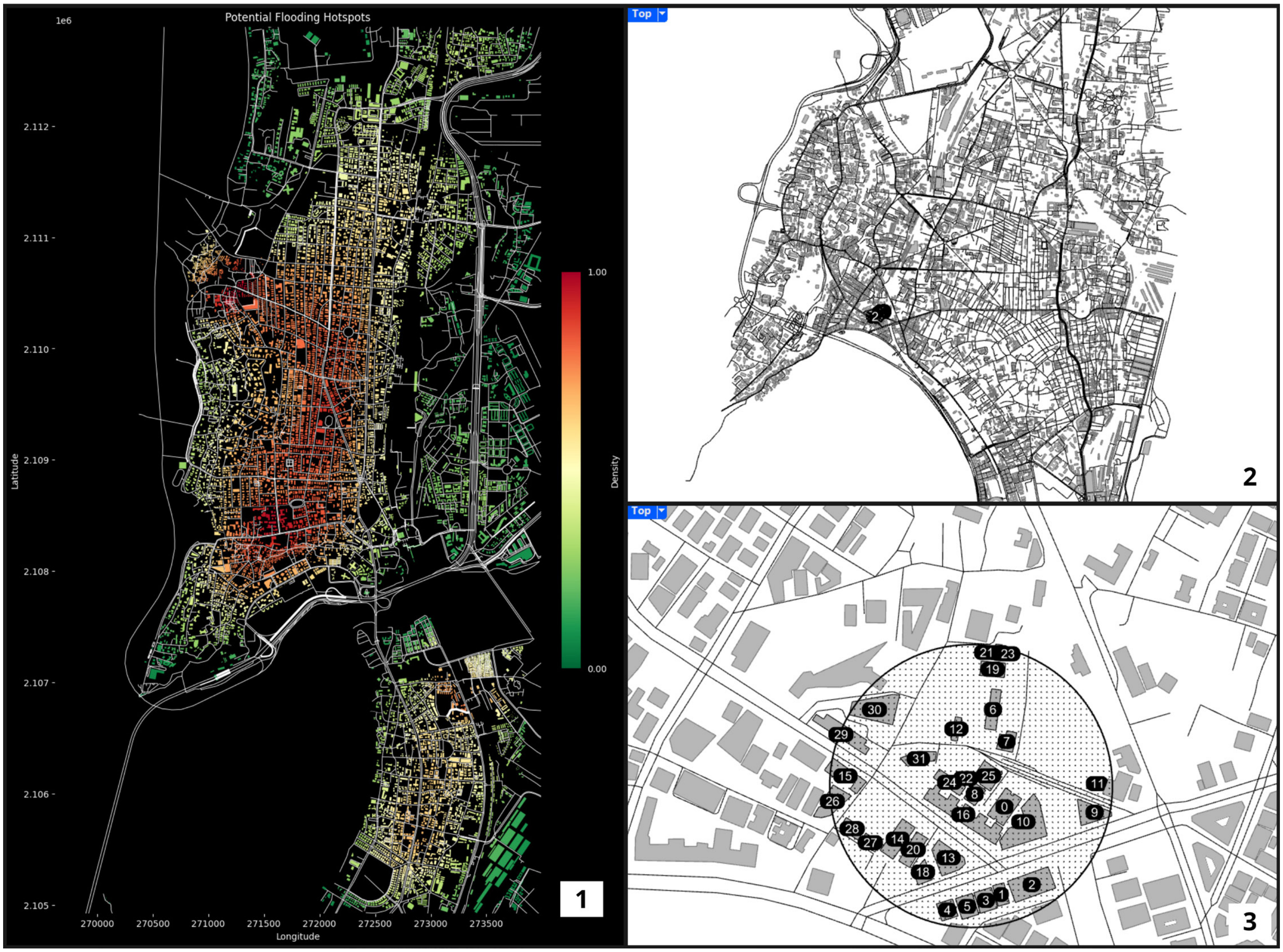
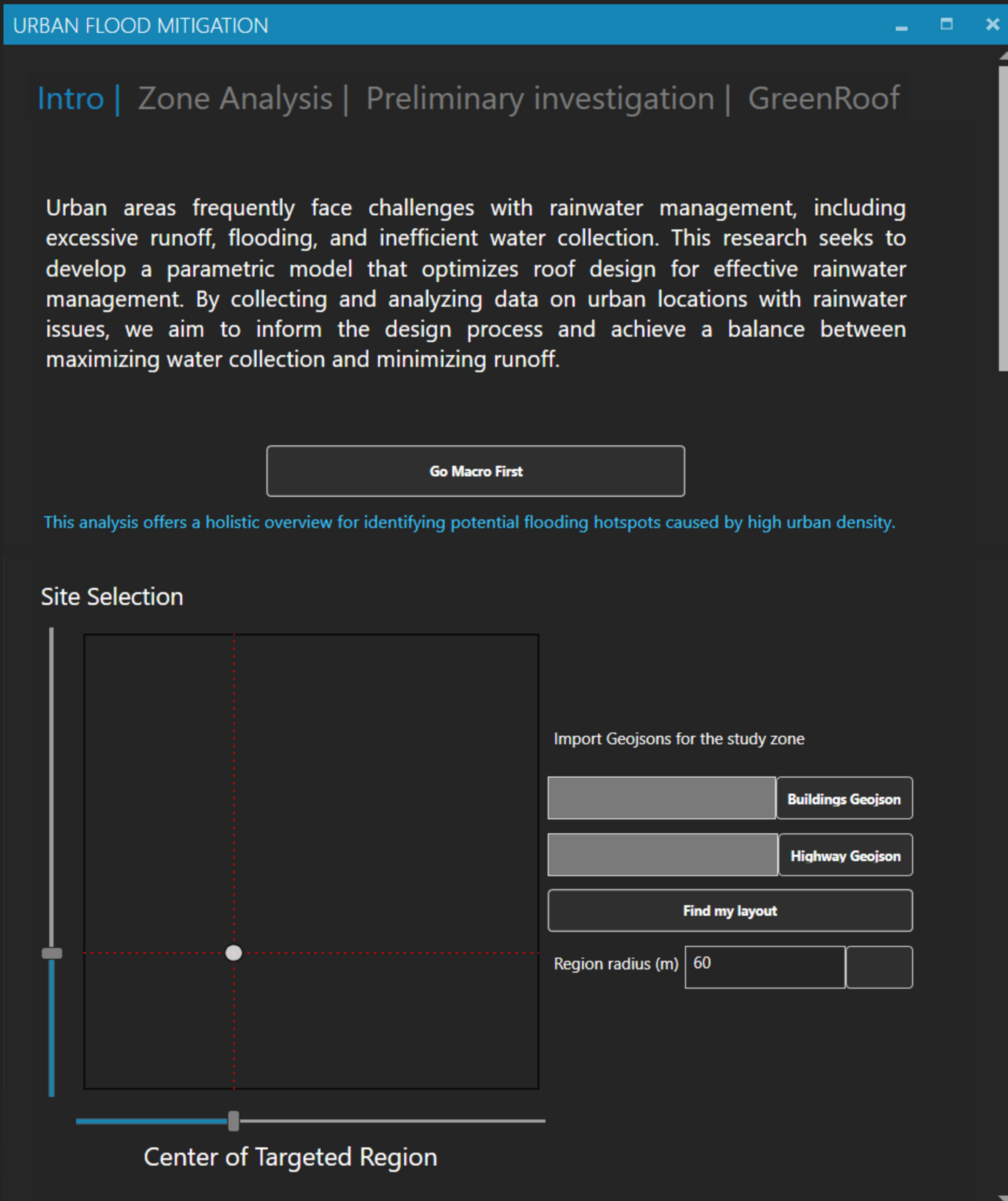


Figure 43: Left: Macro level Colab file output, Top right: Target Region selected, Bottom right: Target Region zoomed in with building tags visible. Made by authors

Welcome to our app generated via **Rhino (8), Grasshopper and Human Ui**, also with the help of a few more plugins.

To access our app you will download our package through **github** in the link below or through google drive also on the link below, and when starting grasshopper please insure that you download all the plugins listed here.

Now diving into the app, when opening our grasshopper script this window will automatically popup and you can read this explanation of our aim, through the first section you can choose to **"Go Macro First"** button that will take you to our **Colab Notebook** were you can adjust a zone of study and visualize a plot that will investigate the critical hotspots in the chosen zone and also download Geojson files, getting back to grasshopper the user can import the downloaded Geojson files or use their own, after that selecting **"find my layout"** will relocate the view port to the layout, at this point the user can freely choose a point with the MD slider on his map and also adjust the radius of the selected Region.


URBAN FLOOD MITIGATION
Intro | Zone Analysis | Preliminary investigation | GreenRoof
Urban areas frequently face challenges with rainwater management, including excessive runoff, flooding, and inefficient water collection. This research seeks to develop a parametric model that optimizes roof design for effective rainwater management. By collecting and analyzing data on urban locations with rainwater issues, we aim to inform the design process and achieve a balance between maximizing water collection and minimizing runoff.
Go Macro First
This analysis offers a holistic overview for identifying potential flooding hotspots caused by high urban density.
Site Selection
Import Geojsons for the study zone
Buildings Geojson
Highway Geojson
Find my layout
Region radius (m)
60
Center of Targeted Region

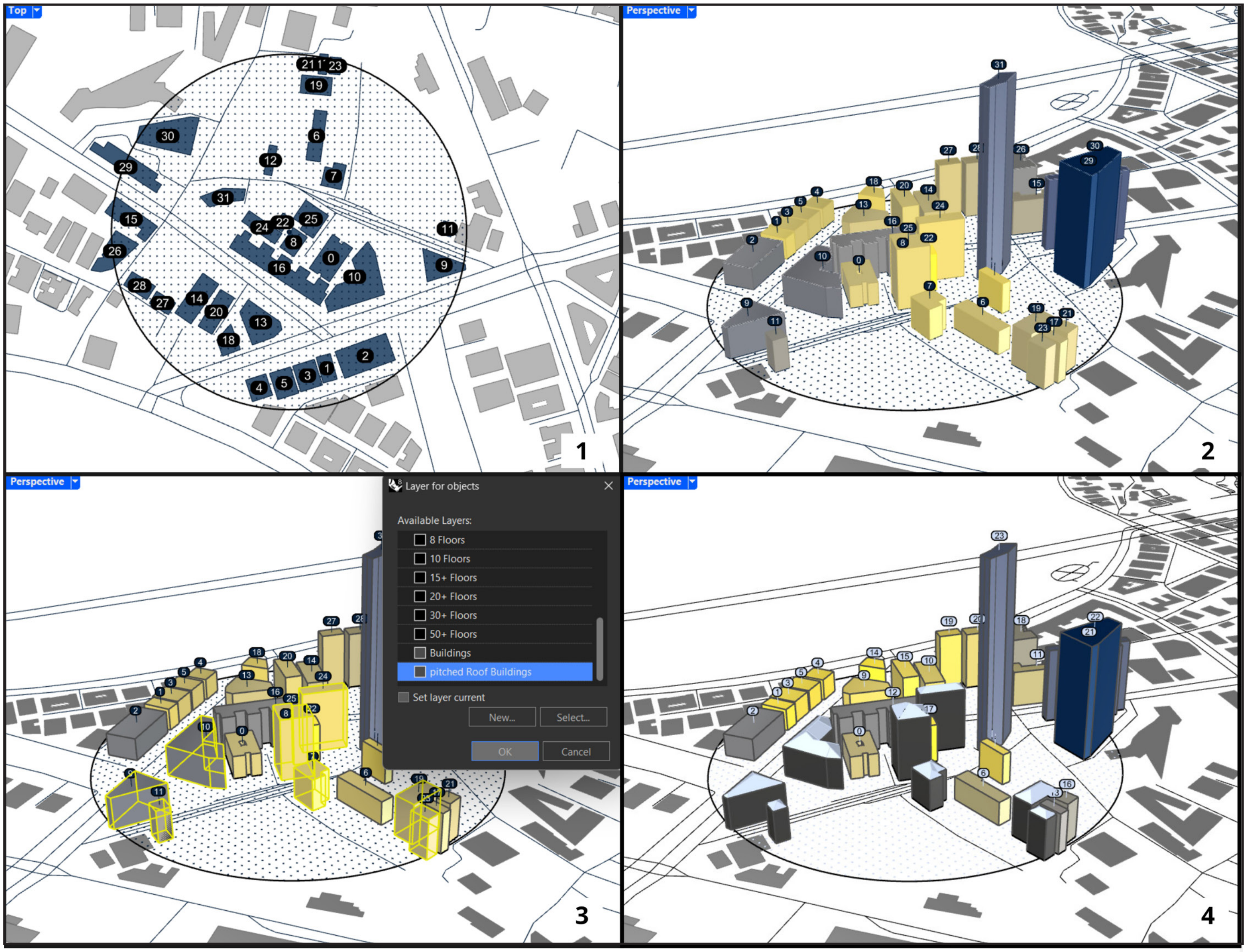
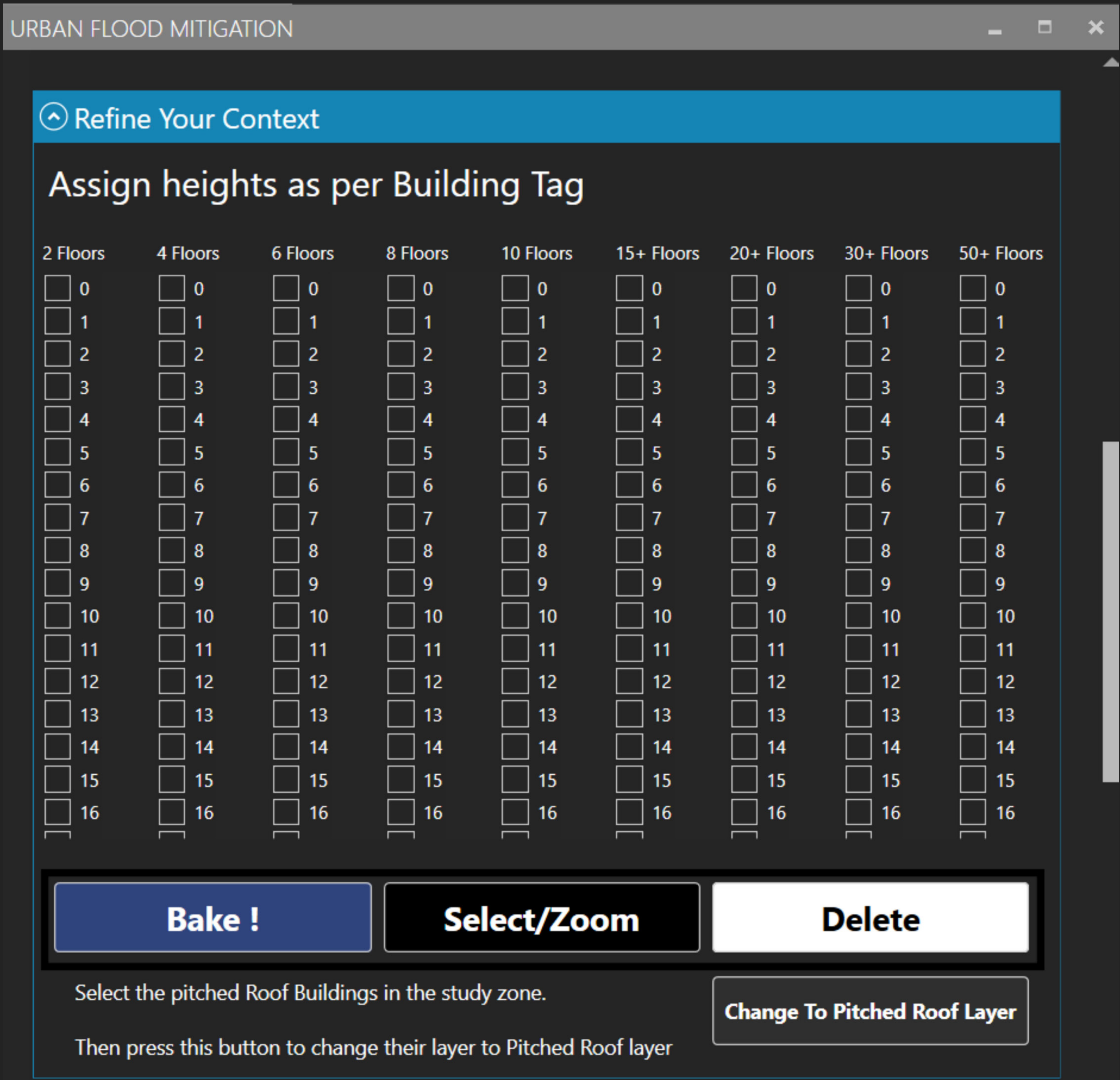


Figure 44: Rhino viewport - Heights assigned as per building tags. Made by authors.

A way to refine the context and to have a more realistic results, the user is provided with this checklist to mark the building according to their tags seen on the view port. After the user finishes this, by pressing "Bake!" Twice the buildings will appear with the heights assigned.

By simply selecting the buildings on rhino view port and hitting the "change to pitched roof layer" button you can separate the pitched roofed buildings from the flat roofed ones. Users can also select to zoom in again if lost in the view port or select then delete if they want to adjust the heights again.

Note: pitched roofed buildings are not taken in consideration in our current solutions seen in the next steps, stay tuned for new updates regarding that.


URBAN FLOOD MITIGATION
Refine Your Context
Assign heights as per Building Tag
2 Floors
4 Floors
6 Floors
8 Floors
10 Floors
15+ Floors
20+ Floors
30+ Floors
50+ Floors
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Bake !
Select/Zoom
Delete
Select the pitched Roof Buildings in the study zone.
Then press this button to change their layer to Pitched Roof layer
Change To Pitched Roof Layer

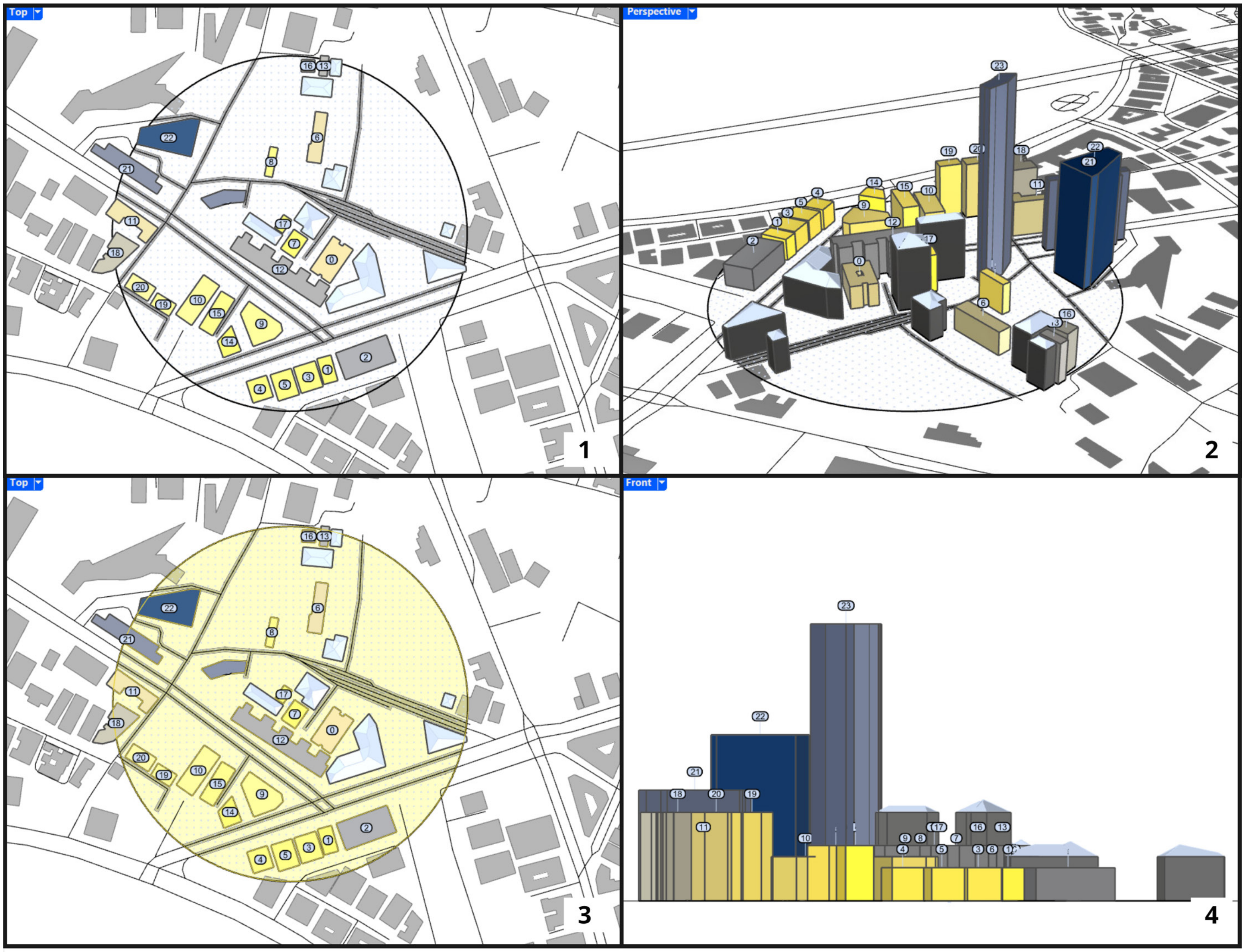
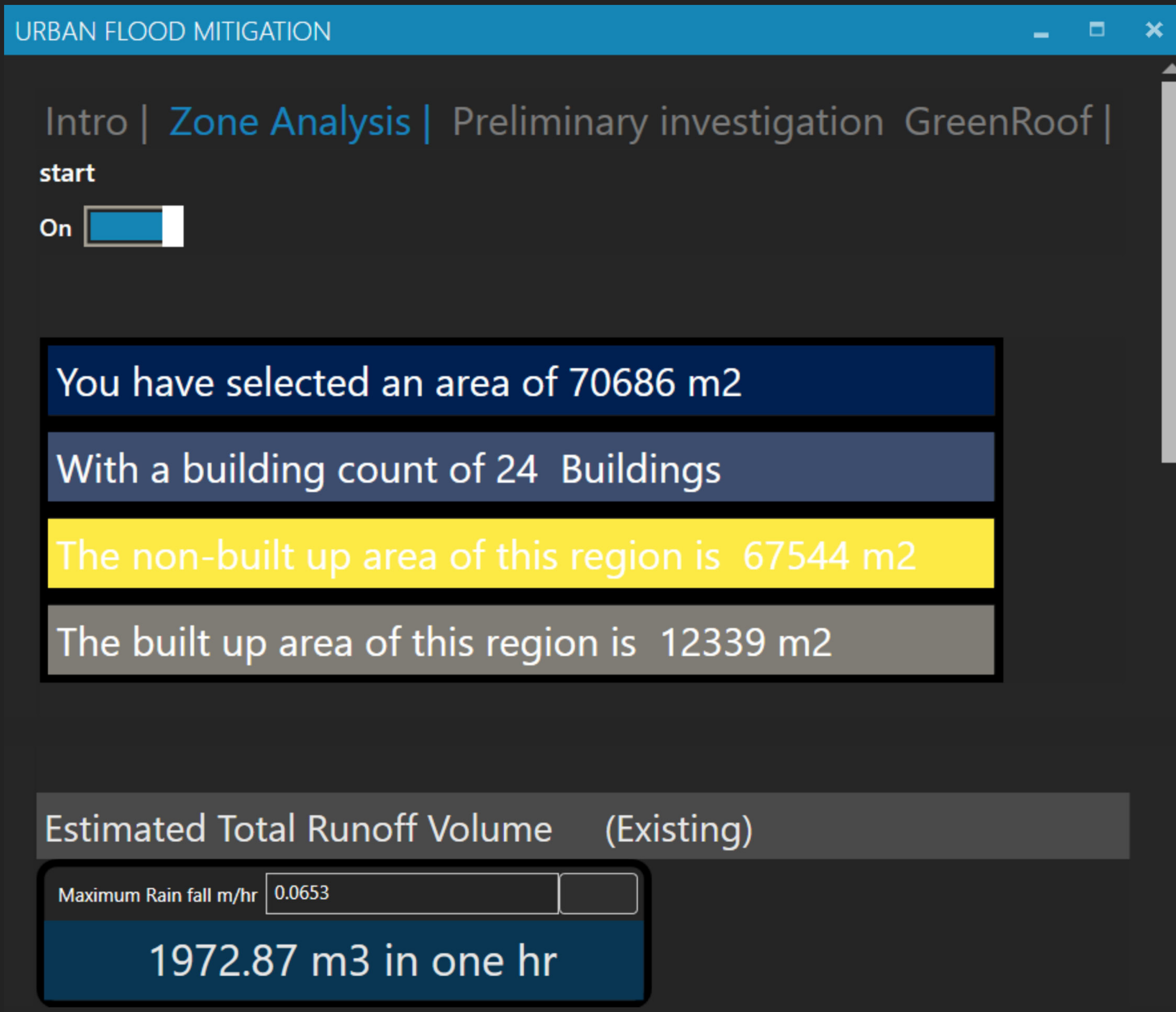


Figure 45: Rhino viewport - Zone Analysis. Made by authors.

Moving on from the "Intro" tab to the "Zone Analysis" tab and by pressing the Start button, you will get these analytical values of **Region Area, Building Count, Area of Non-built surfaces and the built up area**.

Separating these surfaces and calculating this area helps estimating as accurate as possible the **Run-off volume** for the selected region according to the **"Maximum Rain fall m/h"** set by the user.

Note: For the Maximum Rain fall m/h don't forget to press the button


URBAN FLOOD MITIGATION
Intro | Zone Analysis | Preliminary investigation GreenRoof |
start
On
You have selected an area of 70686 m2
With a building count of 24 Buildings
The non-built up area of this region is 67544 m2
The built up area of this region is 12339 m2
Estimated Total Runoff Volume (Existing)
Maximum Rain fall m/hr
0.0653
1972.87 m3 in one hr

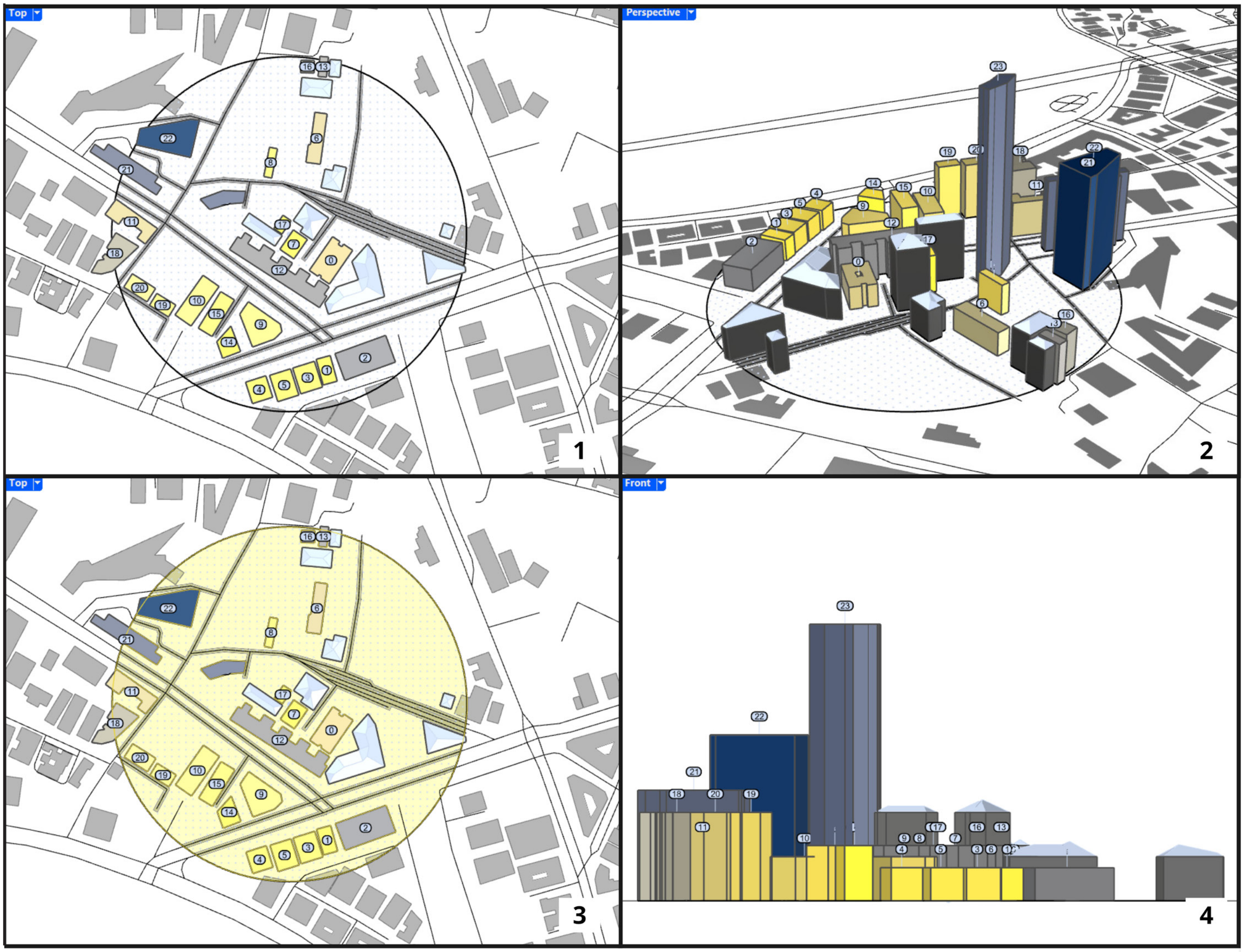


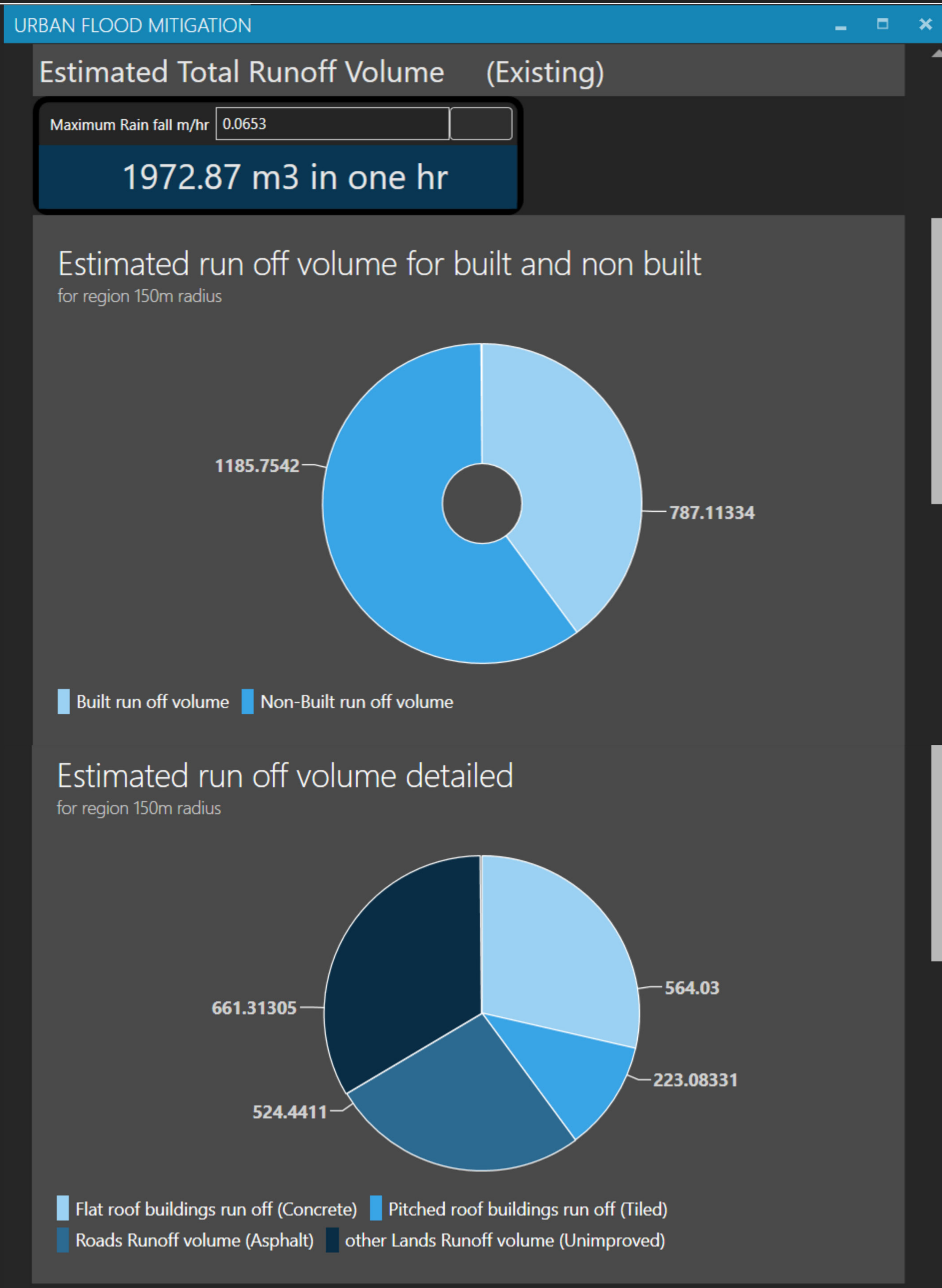
Figure 46: Rhino viewport - Zone Analysis. Made by authors.

To further more analysis for the combination of areas you can check out the pie charts, visualizing the distribution of Runoff Volume according to area of each surface, dividing them into 4 surfaces **[Roads (asphalt), Flat Roofs (Concrete), Pitched roofs (Tiled or brick), Other lands (unimproved)]** , assisting you to tackle more the critical sections.

Run off Coefficients used for our calculations are:

- Concrete =0.70
- Tiled roof (sloped) =0.90
- Asphalt = 0.95
- Unimproved lands = 0.20

More details about run off coefficient can be found in the link below.


URBAN FLOOD MITIGATION
Estimated Total Runoff Volume (Existing)
Maximum Rain fall m/hr
0.0653
1972.87 m3 in one hr
Estimated run off volume for built and non built
for region 150m radius
1185.7542
787.11334
Built run off volume
Non-Built run off volume
Estimated run off volume detailed
for region 150m radius
564.03
223.08331
524.4411
661.31305
Flat roof buildings run off (Concrete)
Pitched roof buildings run off (Tiled)
Roads Runoff volume (Asphalt)
other Lands Runoff volume (Unimproved)

The Next tab is “Preliminary investigation”, This macro-scale model tab provides a streamlined approach to estimate the green roof area required to achieve surface runoff reduction targets, without the need for a detailed 3D model. It serves two main purposes:

1. Estimate Green Roof Area: Quickly estimate the necessary green roof area to meet specified runoff reduction goals.
2. Initial Benchmark: Establish a preliminary benchmark for further design optimization in later stages of your project.

Model Specifications
As detailed in **Chapter 4** the XGBoost model was trained on 1400 samples of neighborhoods with varying urban densities ,and as seen in **Figure 2**,showed a strong diagonal trend,with a R^2 score of 0.981.

Inputs
To use the model, you will need to provide the following inputs:

- Total Building Roof Area: The aggregate area of all building roofs under consideration.
- Green Roof Percentage: The proportion of each roof area that will be converted into a green roof.
- Rainfall Data: Maximum rainfall intensity or total rainfall over a given period.
- Soil Properties: Saturated soil density and other relevant soil characteristics.
- Estimated Green Roof Area: The total area of green roofs required to achieve the runoff reduction targets.

Output

- Runoff Reduction percentage estimate: The estimated reduction in surface runoff based on the implemented green roof areas.

Using the Model

1. Enter Inputs: Fill in the required data fields with accurate information.
2. View Results: Review the estimated green roof area and runoff reduction estimates displayed on the results page.

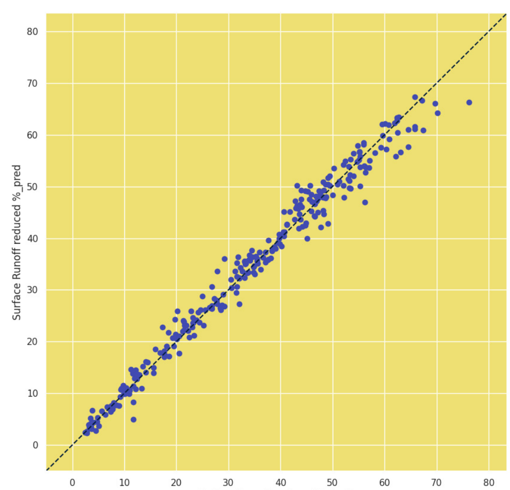
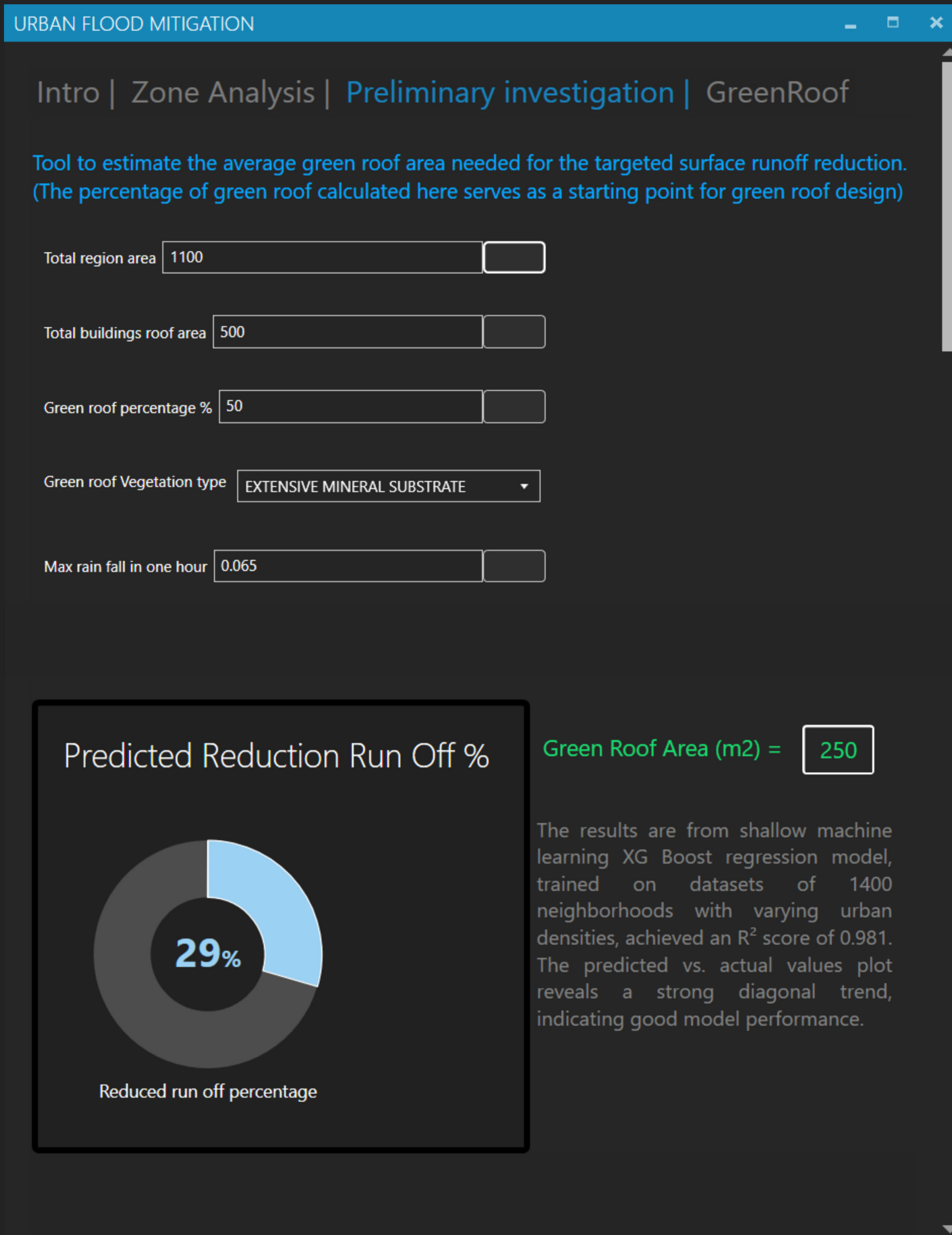


Figure 47: XGBoost Regression Model; chosen for deployment
Hyperparameters: learning rate:0.2, maximum depth: 3, number of estimators: 300 and subsample of 0.8


URBAN FLOOD MITIGATION
Intro | Zone Analysis | Preliminary investigation | GreenRoof
Tool to estimate the average green roof area needed for the targeted surface runoff reduction.
(The percentage of green roof calculated here serves as a starting point for green roof design)
Total region area 1100
Total buildings roof area 500
Green roof percentage % 50
Green roof Vegetation type EXTENSIVE MINERAL SUBSTRATE
Max rain fall in one hour 0.065
Predicted Reduction Run Off %
29%
Reduced run off percentage
Green Roof Area (m2) = 250
The results are from shallow machine learning XG Boost regression model, trained on datasets of 1400 neighborhoods with varying urban densities, achieved an R2 score of 0.981. The predicted vs. actual values plot reveals a strong diagonal trend, indicating good model performance.

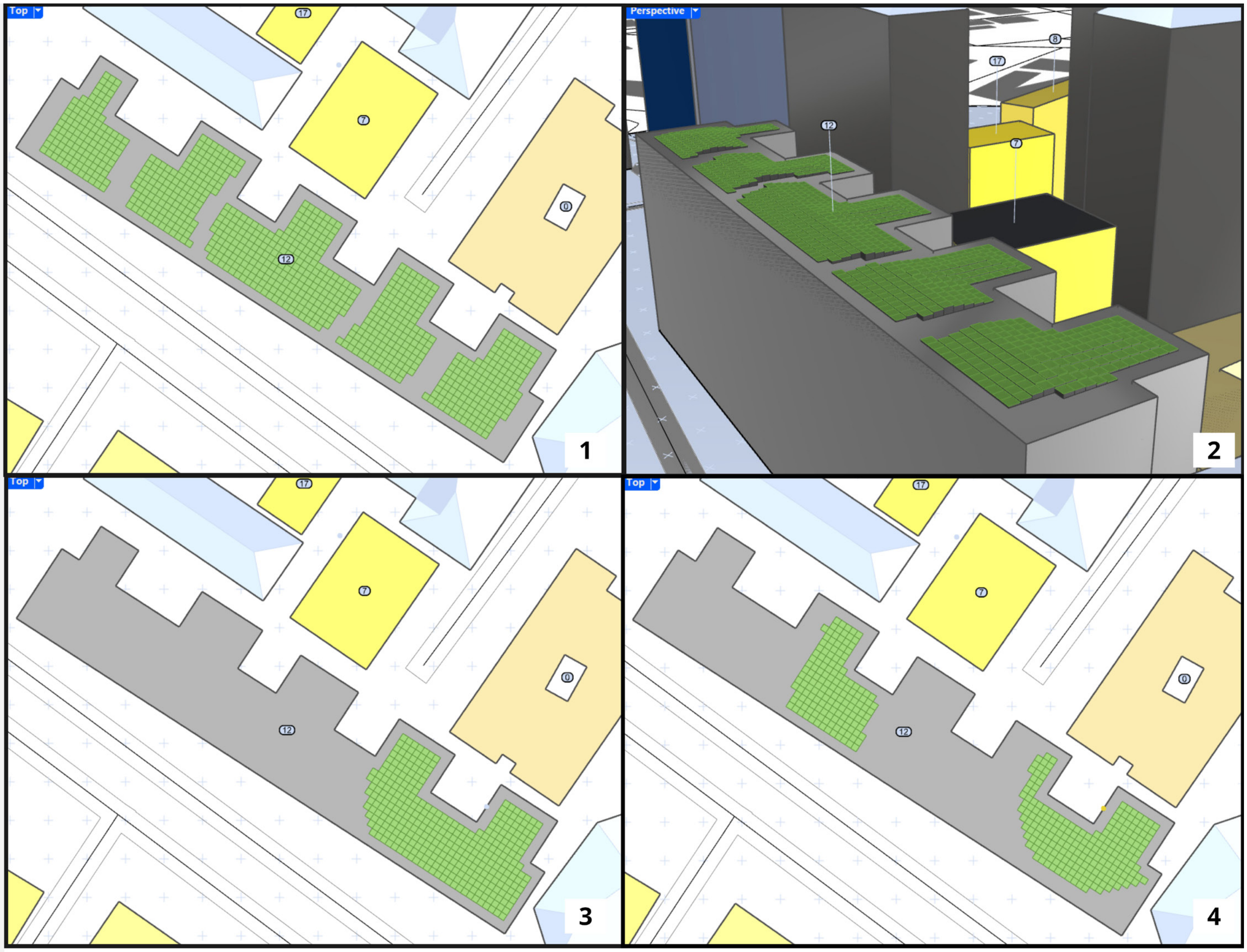


Figure 48: Rhino viewport - Generic green roof division options, top images:divide proposed area equaly and radaily, bottom locate the proposed area manually. Made by authors.

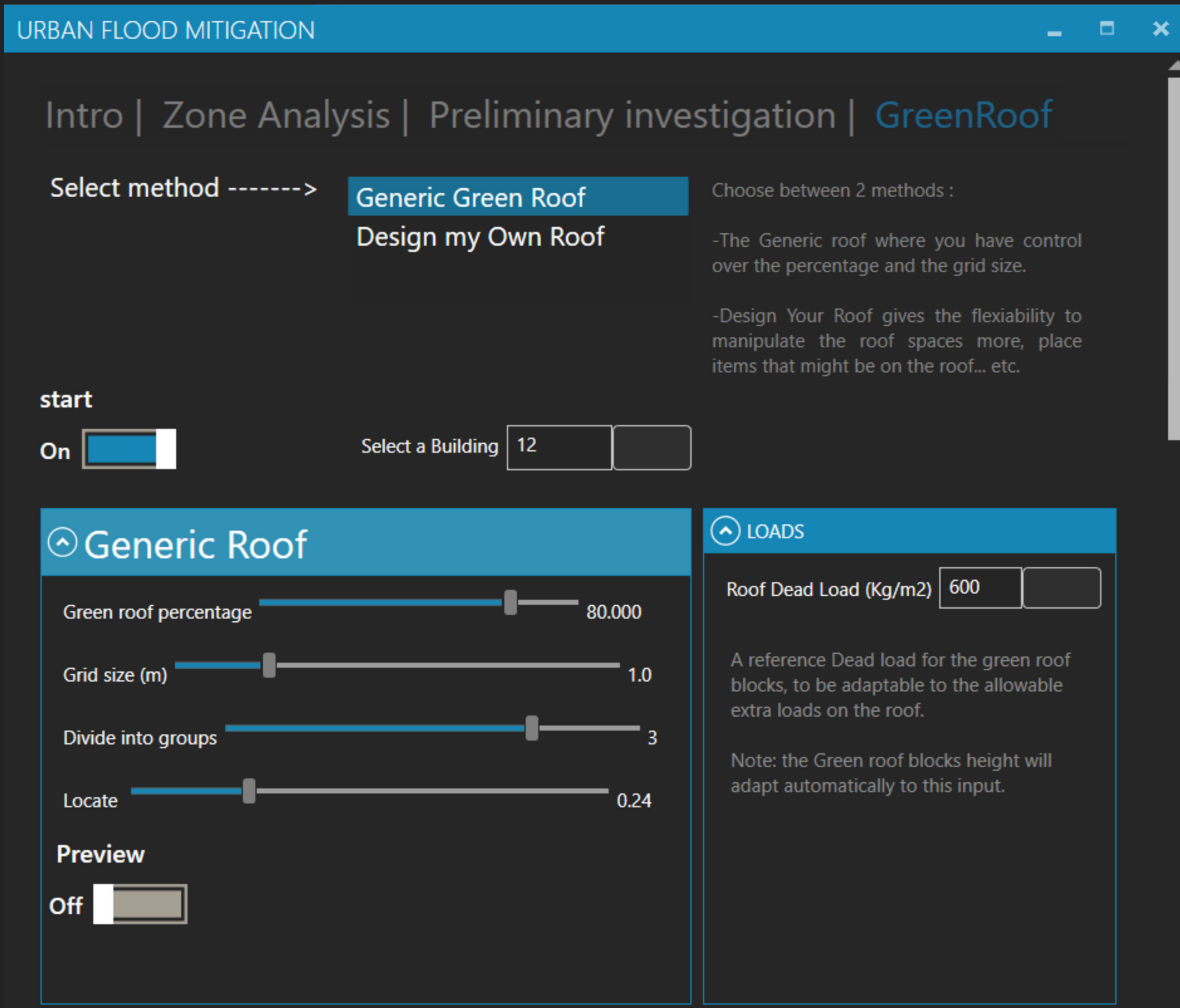
Last but not least the Green Roof tab, there are 2 methods to apply the green roof.

First is a Generic one where you can do the following:

- Set the Green roof percentage.
- Set the Grid size.
- Have your Green roof as one block or divide it into [1, 2, 3, 4] blocks.
- And then you can also locate to a certain point on the edge of the building.

The load part is made to adjust the height to a reasonable load on the building, as the stepped green roof has a range of heights, its made to control the upper bounds of that range if its set less that "600" that we see on the screen the highest box will automatically be lower and lower as the number goes down.

Note: Make sure when you are adjusting your parameters that the preview button is off to be able to have less computational time, and switch it on after you are set with your parameters.



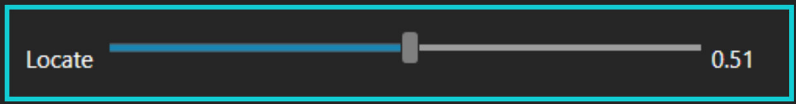


image (3)

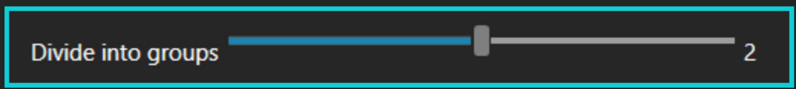


image (4)

Figure 49: Rhino viewport -Design you roof option flow representation. Made by authors.

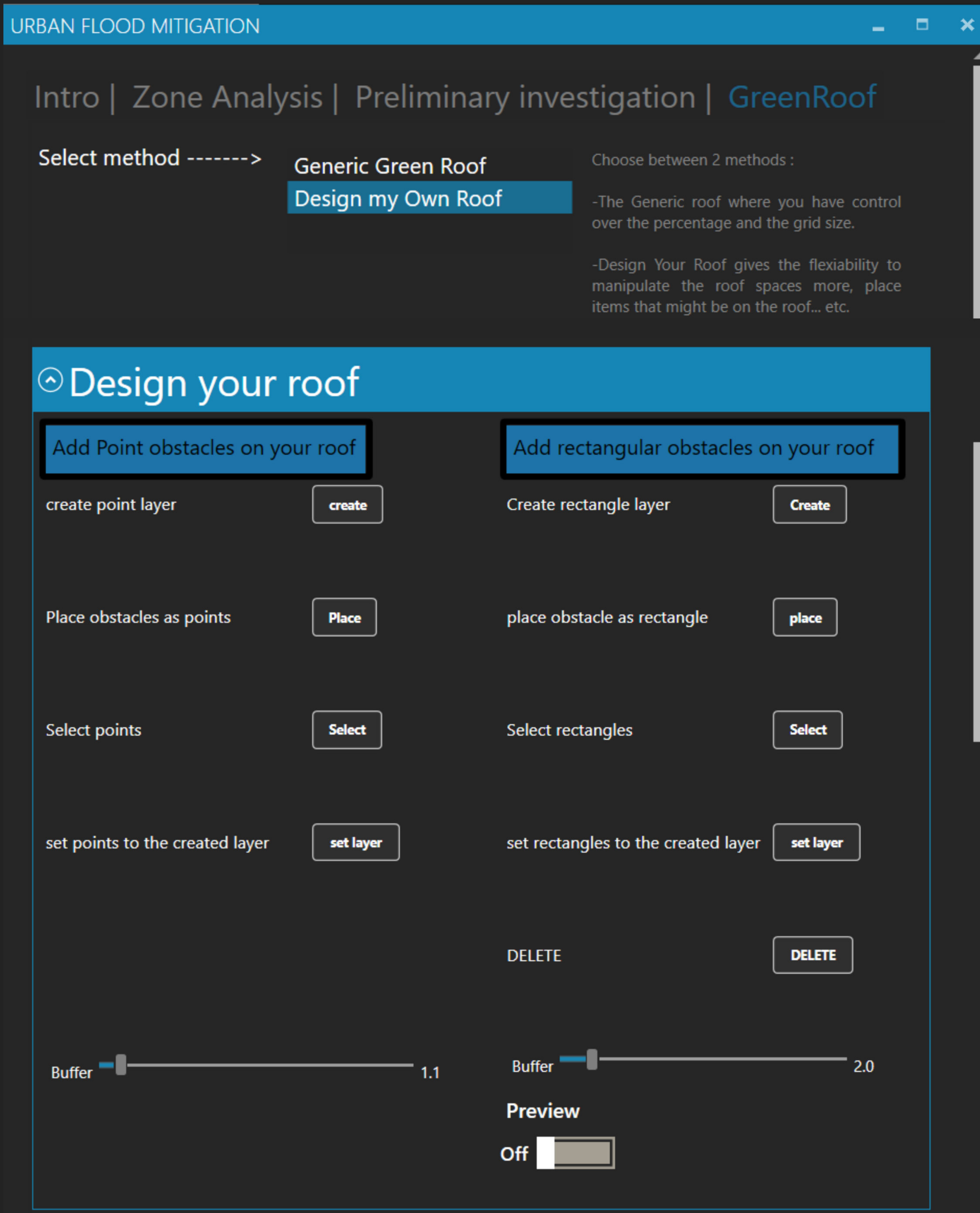
Secondly is the **“Design your roof”**, because in most cases we don’t have these **ideal roof spaces** as we saw before and usually we have a **Stair case room, AC units or Chillers**. So the user can actually set these as they wish by adding points or rectangles (preferable on the top view port).

By create then place the point buttons, you can place points on the roof layout and then select them by the select button and change their layer to the **“Point obstacle layer”**, and same thing for the Rectangle but setting them to the **“Rectangle Obstacle layer”**.

A delete button can be used for the selected geometries to draw them again.

The user can adjust the buffer around the drawn geometries above the roof.

Note: Make sure when you are adjusting your parameters that the preview button is off to be able to have less computational time, and switch it on after you are set with your parameters.


URBAN FLOOD MITIGATION
Intro | Zone Analysis | Preliminary investigation | GreenRoof
Select method ------->
Generic Green Roof
Design my Own Roof
Choose between 2 methods :
-The Generic roof where you have control over the percentage and the grid size.
-Design Your Roof gives the flexiability to manipulate the roof spaces more, place items that might be on the roof... etc.
Design your roof
Add Point obstacles on your roof
Add rectangular obstacles on your roof
create point layer
create
Create rectangle layer
Create
Place obstacles as points
Place
place obstacle as rectangle
place
Select points
Select
Select rectangles
Select
set points to the created layer
set layer
set rectangles to the created layer
set layer
DELETE
DELETE
Buffer
1.1
Buffer
2.0
Preview
Off

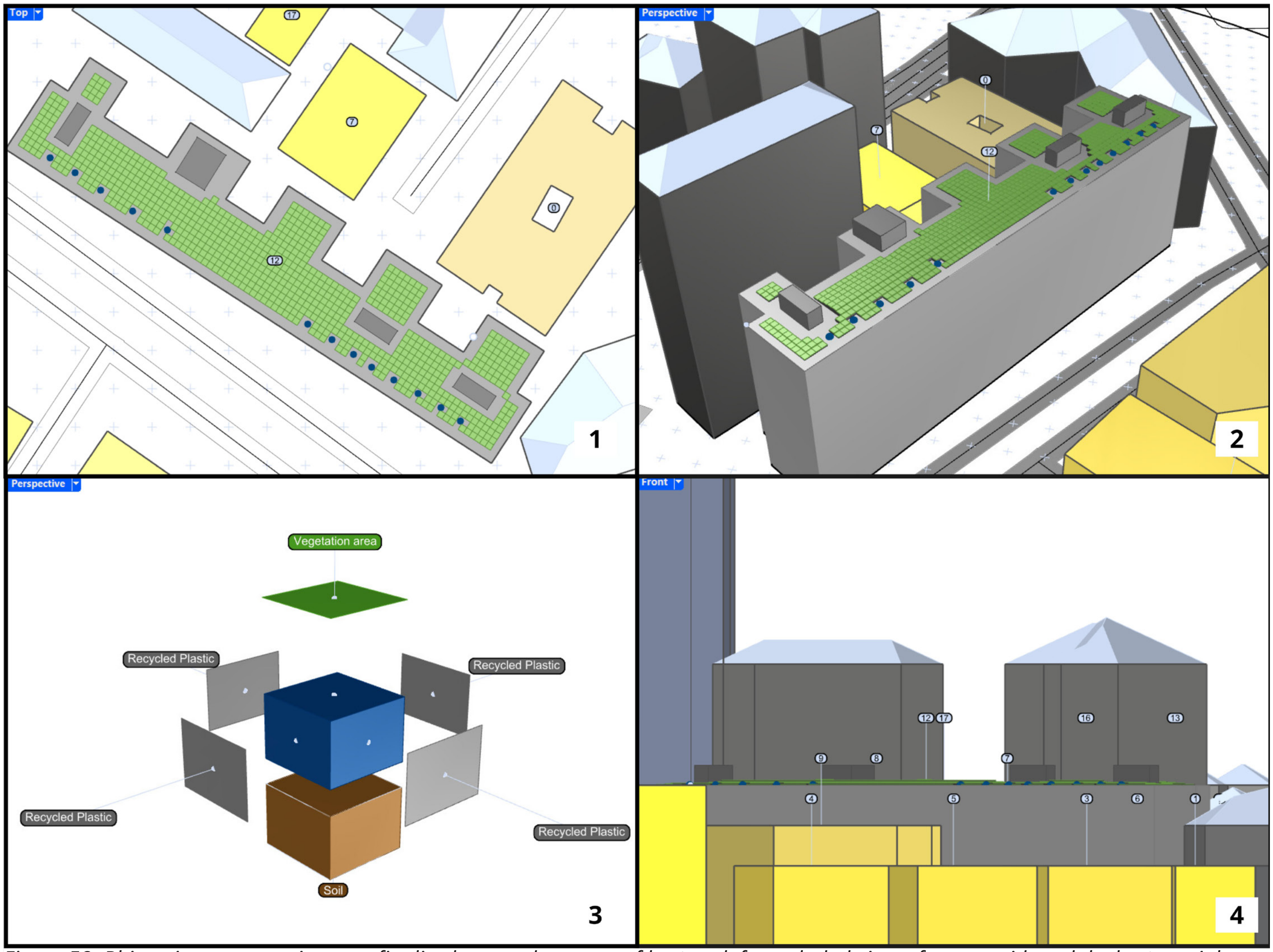


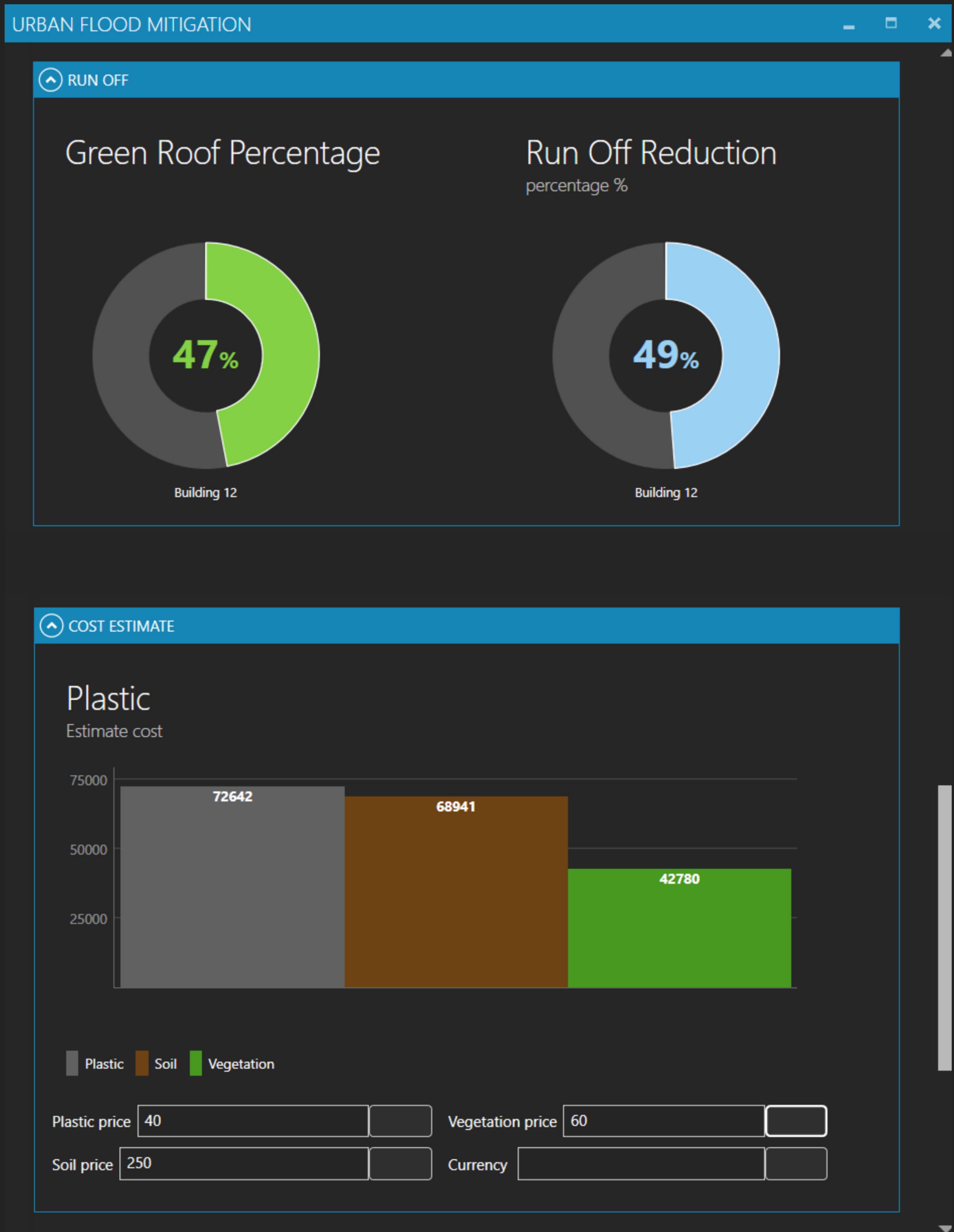
Figure 50: Rhino viewport -top images: finalized stepped green roof bottom left: exploded view of green grid module, bottom right: side view of stepped green roof. Made by authors.

After setting up the Green roof a Run off Analysis is made for the exact percentage of Green roof implemented, and this calculation is taking also into consideration the average height of the modular Green roof boxes.

An Estimated material Cost is generated from breaking down elements of each module (box) to have them as follows:

- Plastic sides of the box in m2.
- Soil the volume of the box in m3.
- The vegetation as the top side in m2.

At the end also the user can set the currency they prefer.


URBAN FLOOD MITIGATION
RUN OFF
Green Roof Percentage
47%
Building 12
Run Off Reduction
percentage %
49%
Building 12
COST ESTIMATE
Plastic
Estimate cost
75000
50000
25000
72642
68941
42780
Plastic
Soil
Vegetation
Plastic price
40
Vegetation price
60
Soil price
250
Currency

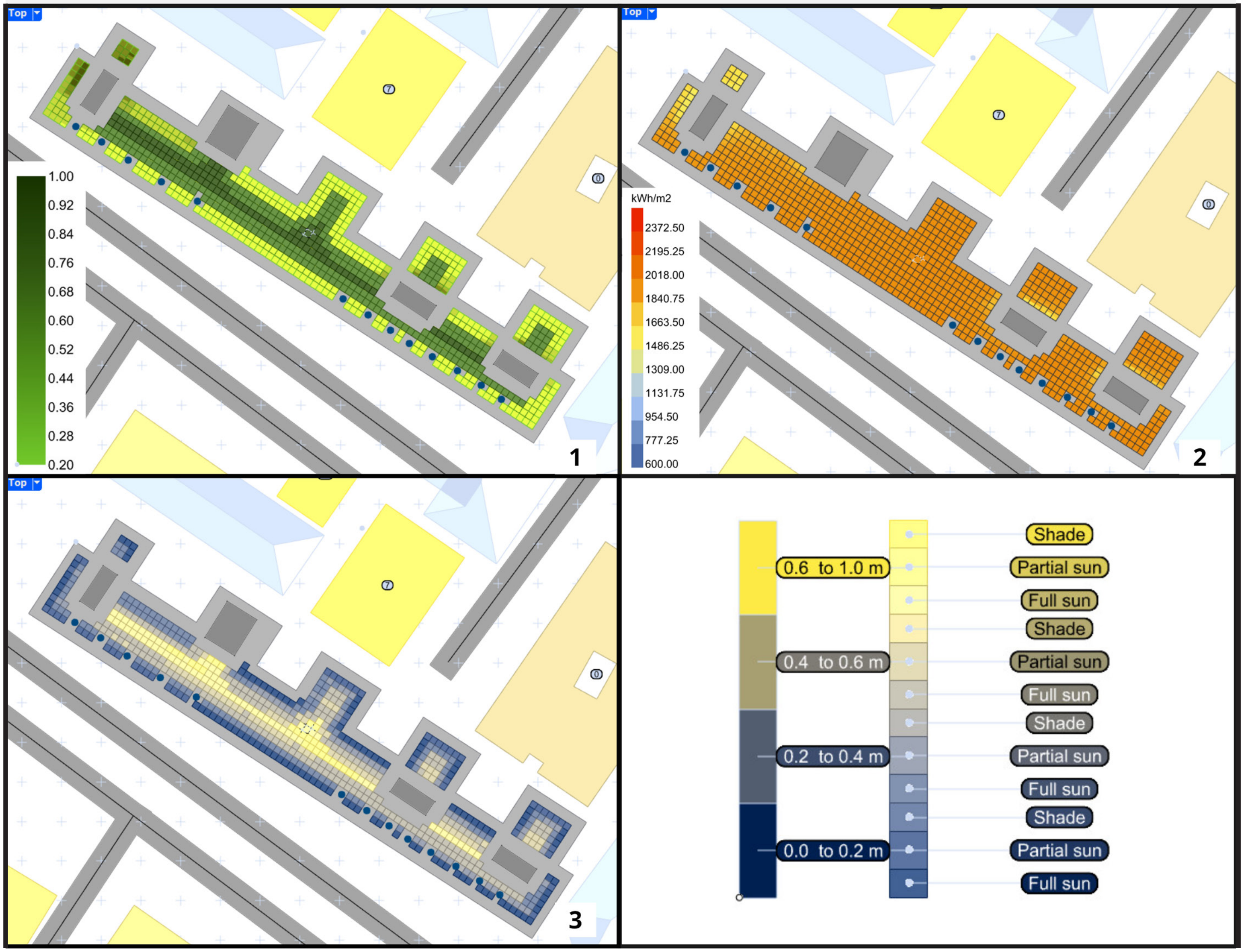


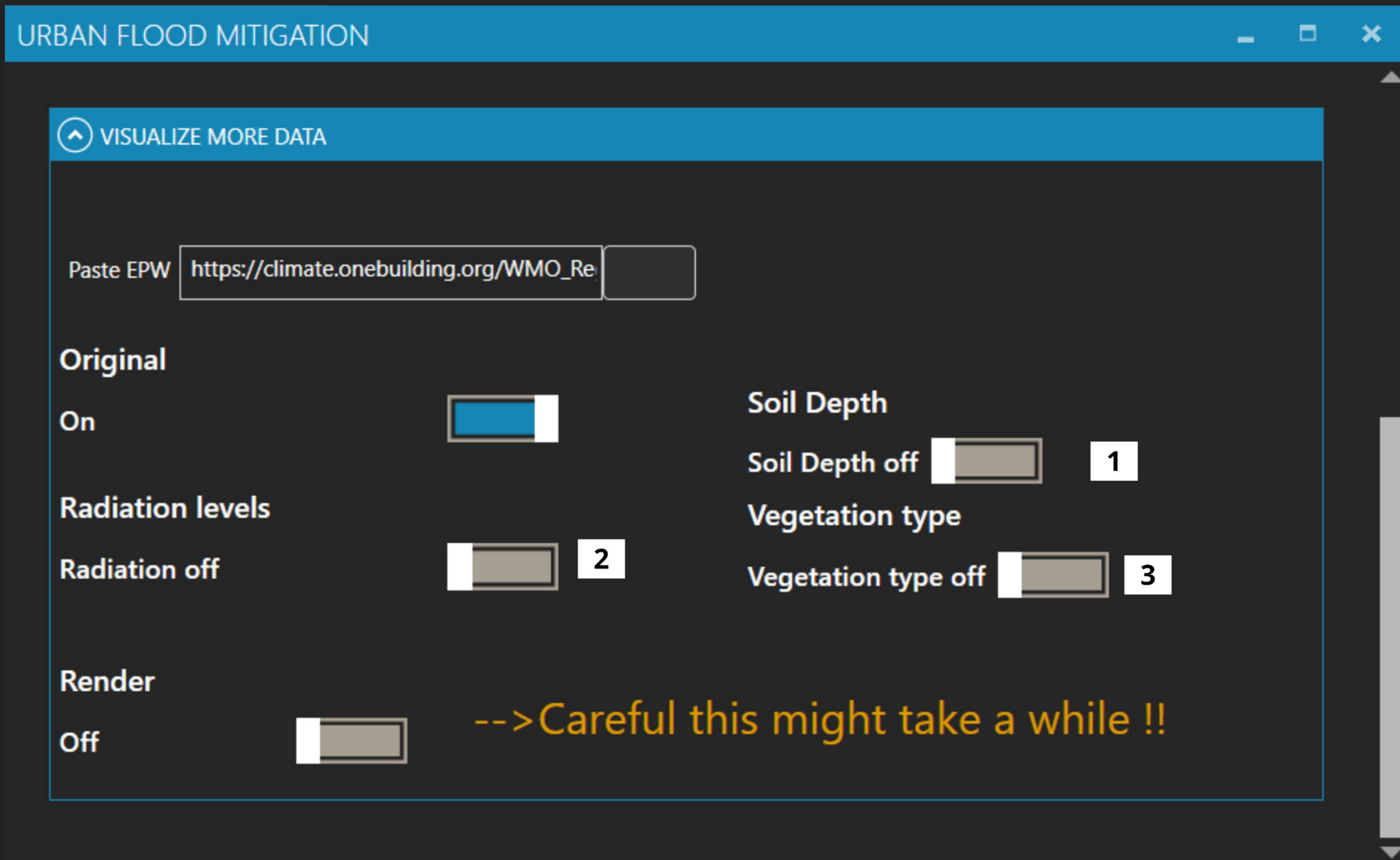
Figure 51: top left- soil depth variation of green roof, top right: incident solar radiation mapped on the green roof, bottom left: green roof mapped as per depth and radiation with legend in bottom right. Made by authors.

Finally the Visualizing section, where the user can analyses 3 main parts which are:

- Soil Depth
- Radiation levels
- Vegetation Types

The user is required to get an EPW (weather file) to get the results of the radiation and have more accurate suggestion for the vegetation types.

About the vegetation types suggestion they are made following the criteria shown above, combining 2 factors the soil depth and the radiation all together, to suggest **Grass, Plants, Shrubs or Trees**.


URBAN FLOOD MITIGATION
VISUALIZE MORE DATA
Paste EPW
https://climate.onebuilding.org/WMO_Re
Original
On
Radiation levels
Radiation off
2
Soil Depth
Soil Depth off
1
Vegetation type
Vegetation type off
3
Render
Off
-->Careful this might take a while !!

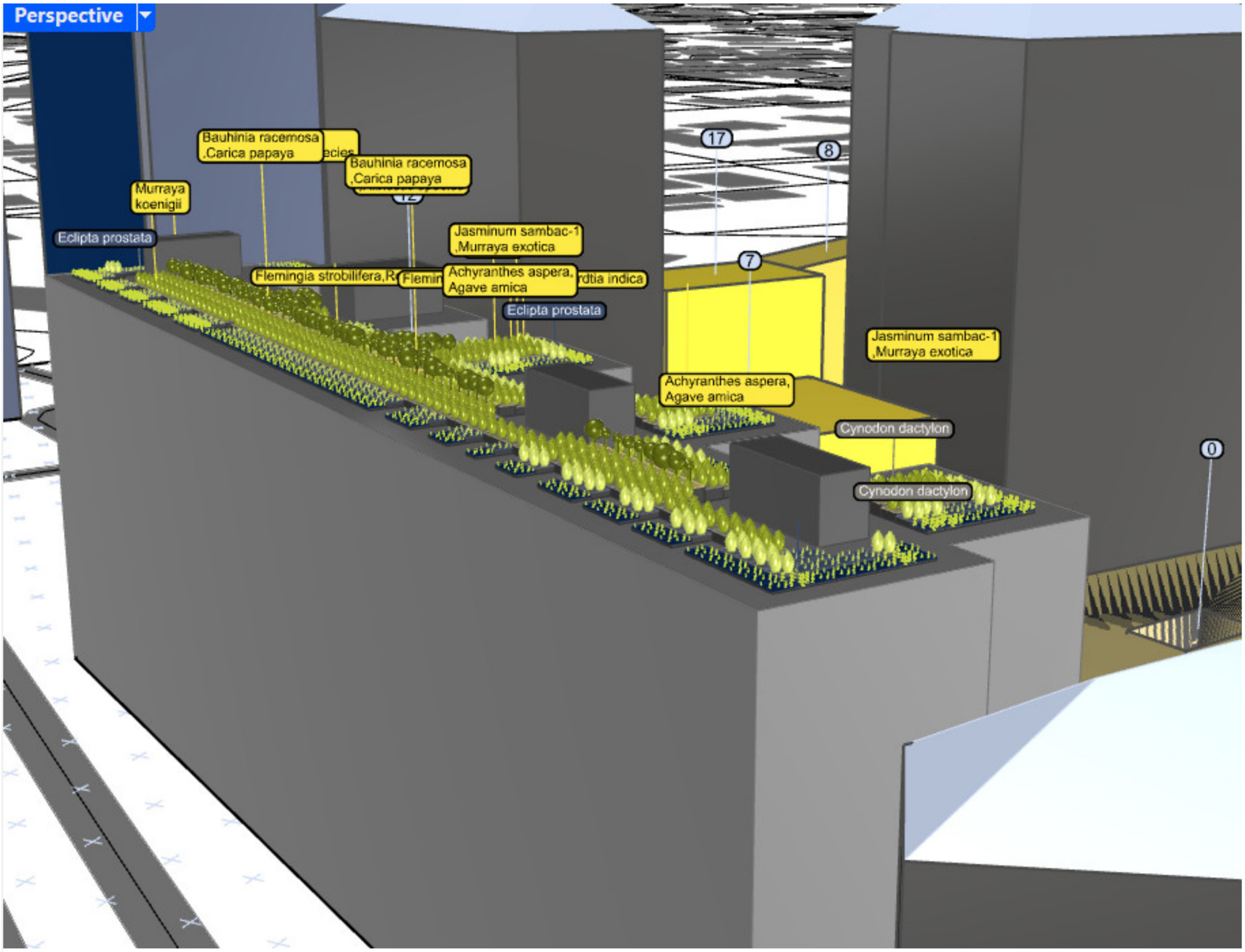
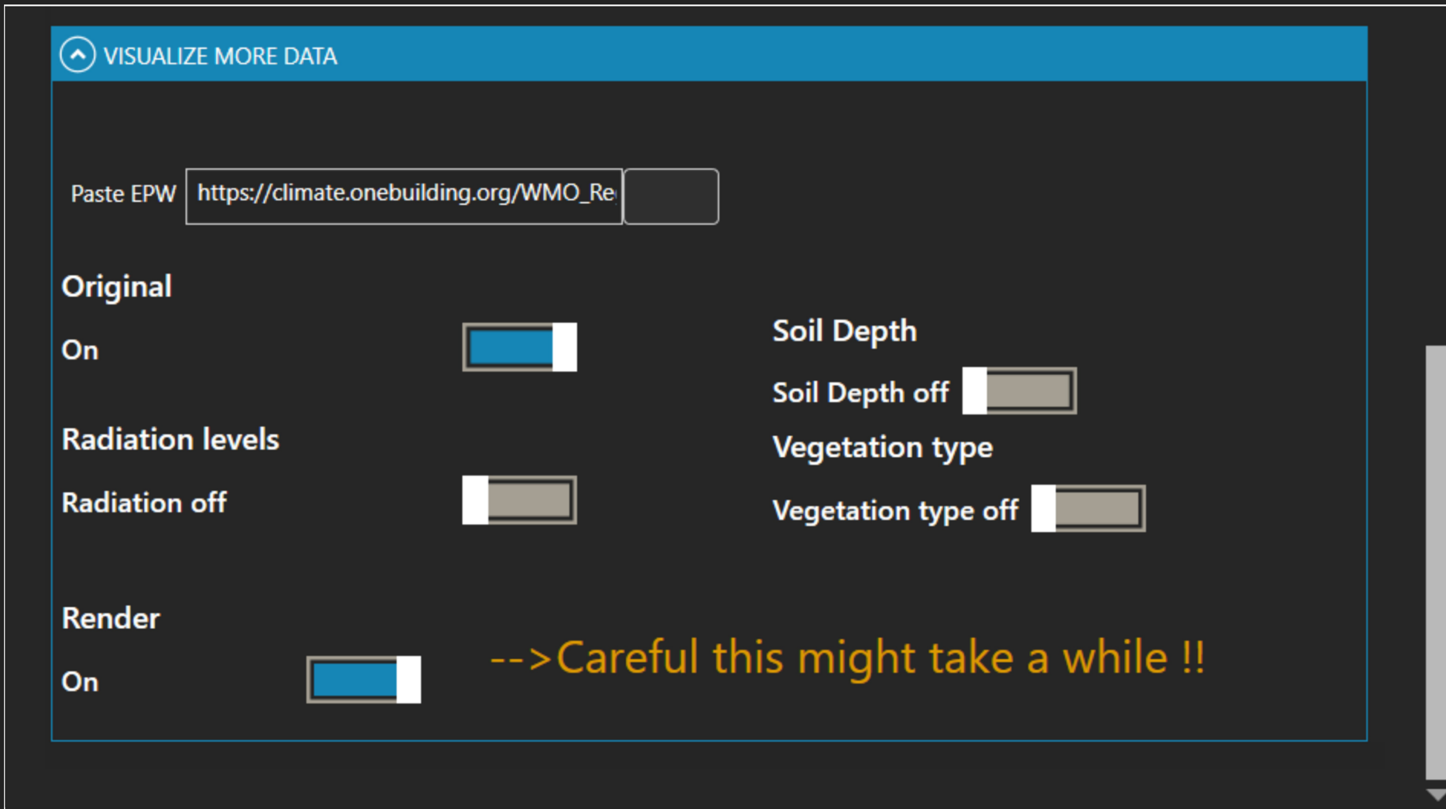


Figure 52: perspective view of target green roof with vegetation render and name tags. Made by authors

An a the “Render” button should be only pressed when ready because it takes some computational power so (not recommended if you have a huge green roof area) .

That is it for our application explanation, also the video tutorial in the link below.

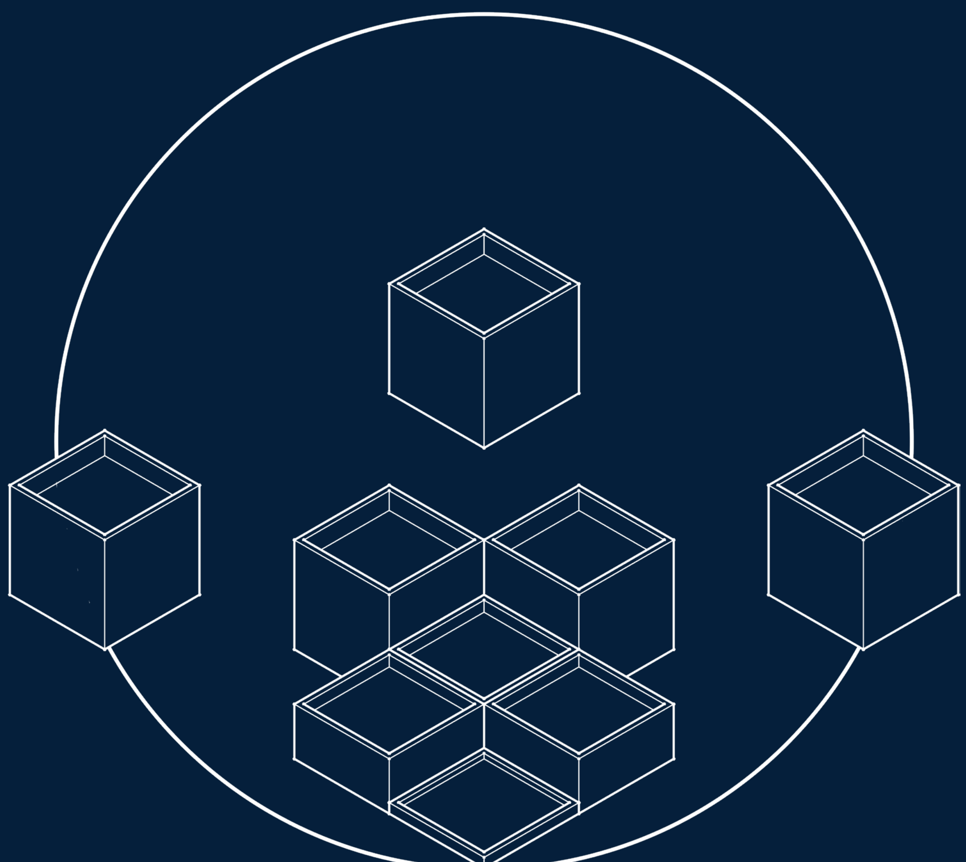
Tutorial link : https://drive.google.com/drive/folders/1y1NHBHXCN6ycNErkSaZ6L0JfJIkq8ZAn?usp=drive_link


VISUALIZE MORE DATA
Paste EPW
https://climate.onebuilding.org/WMO_Re
Original
On
Soil Depth
Soil Depth off
Radiation levels
Vegetation type
Radiation off
Vegetation type off
Render
On
-->Careful this might take a while !!

CHAPTER 7

FUTURE WORK AND RE-SEARCH DIRECTIONS

7.1. Future Potential
7.2. Tensile



FUTURE POTENTIAL
To the Work Flow

Digging deep into our tool and testing it, it is noticed in various cases in Tardeo, Mumbai (our case study zone) that pitched roof buildings and streets gets a good portion of the run off volume.

Further Inclusions:

- Including an adaptive solution to pitched roofs, would further improve our approach to mitigate urban flash floods through the conversion of impervious surfaces to permeable surfaces.
- Including an adaptive solution to large open street spots like street intersections and crossings, would greatly impact the reduction of run off through the non-built area

Although these 2 suggested methods are packed with their own constraints and was challenging to tackle we started off with a proposal to include a tensile structure solution for the open street areas that was held off due to our limited time research.

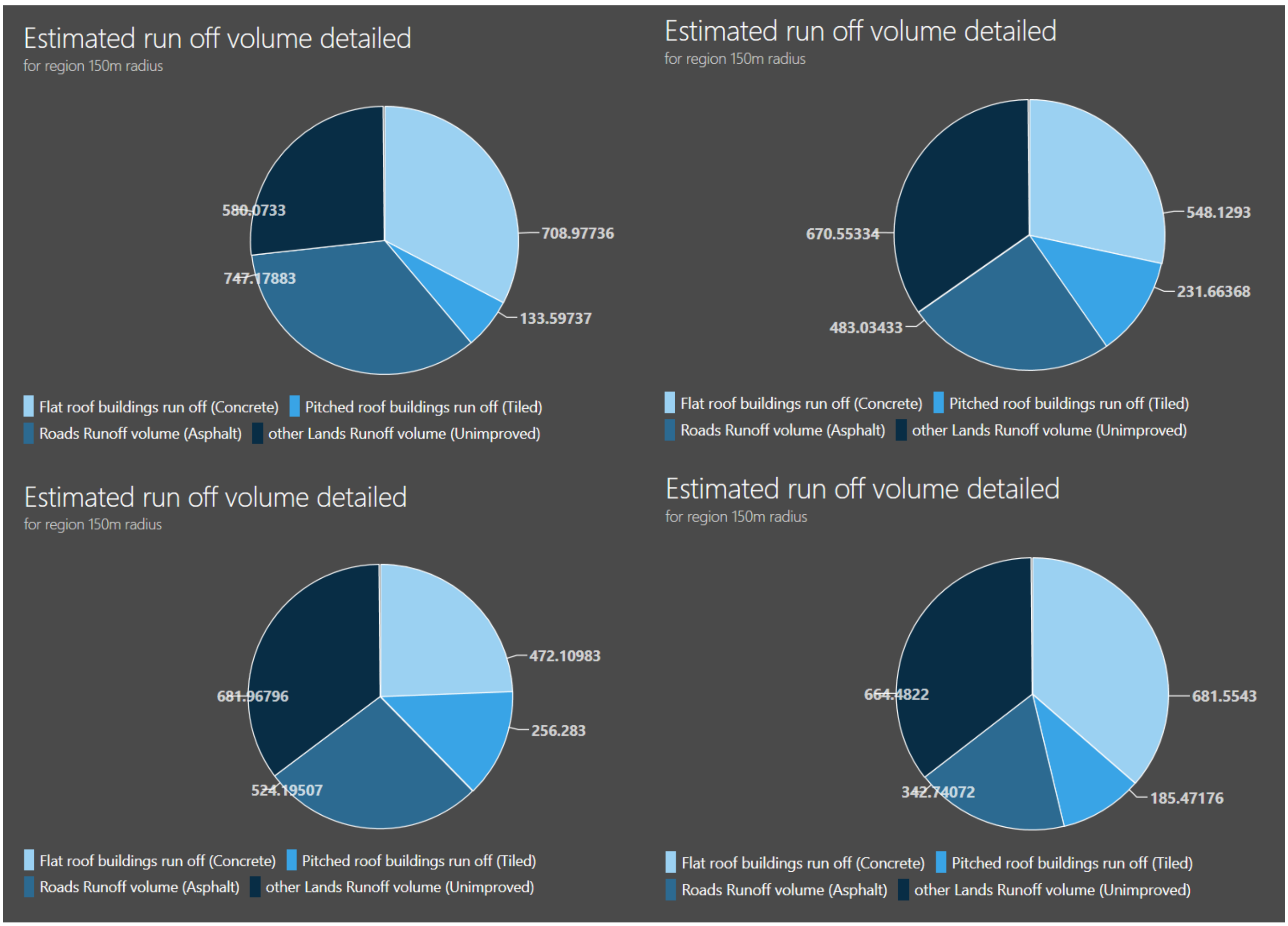
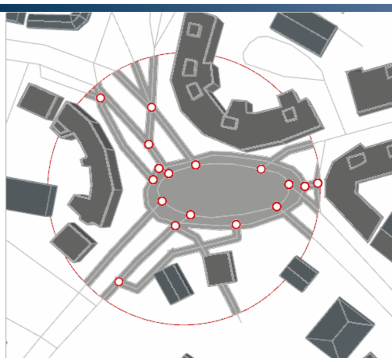
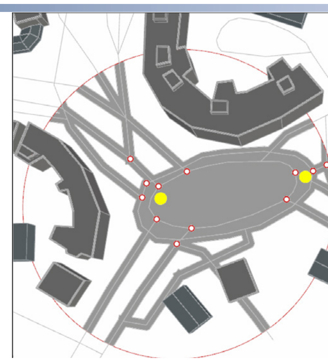


Figure 53: Zone analysis pie chart. Made by authors.

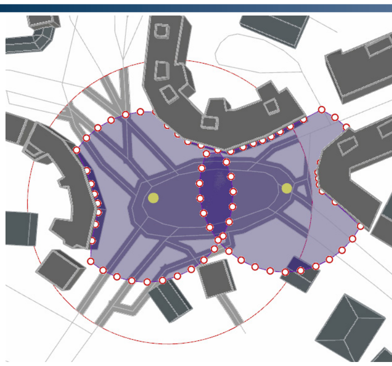
TENSILE



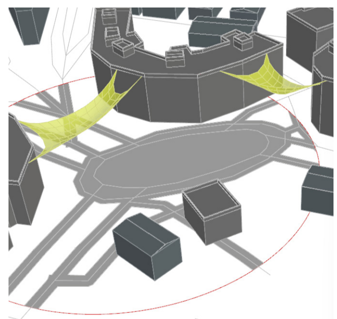
Analyzing Road lines intersections, to target streets intersections or squares.



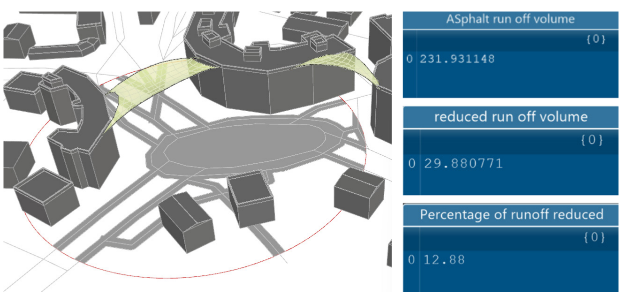
Average point for multiple intersections.



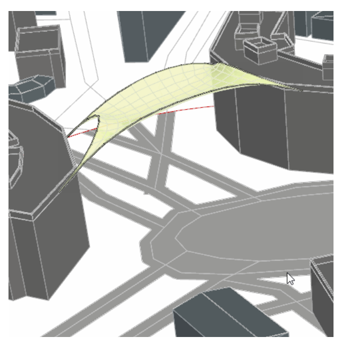
Using iso-vist to get tensile surface and support on neighboring buildings.



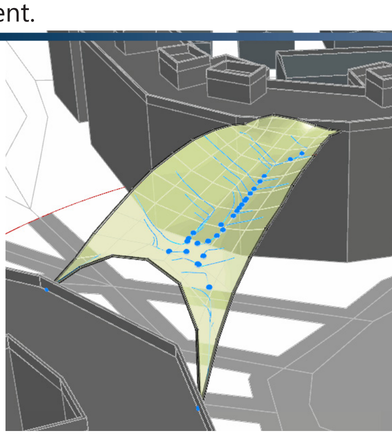
With kangaroo physics we simulate the tensile structure mesh.



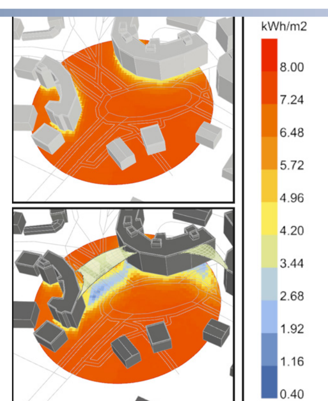
Calculate the run off volume reduced from the tensile component.



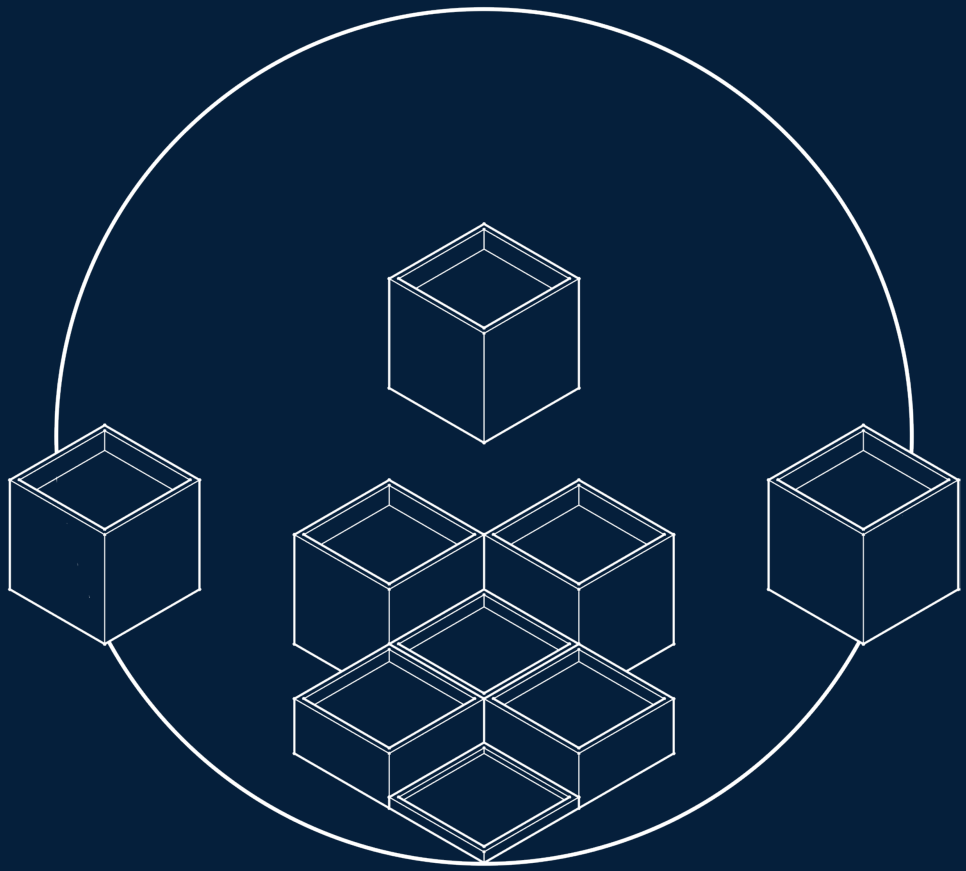
To avoid tension on the surrounding buildings creating arch structures for the tensile membrane.



Simulate the rain water direction.



Overview the Radiation on the selected region.



CHAPTER 8
CONCLUSION

CONCLUSION

This thesis has explored the multifaceted challenges urban neighbourhoods face in managing rainwater, driven by the growing impacts of climate change, urbanization, and inadequate infrastructure. Through the development of an innovative work flow combining parametric and performance-driven design methods, this research has demonstrated effective strategies for enhancing rainwater absorption and mitigating urban flooding risks.

The proposed design strategies prioritize rainwater management, ensuring that excess runoff during heavy rainfall is absorbed and redirected efficiently. By incorporating flexible and responsive design methods, adaptable to various rainfall conditions and site-specific characteristics, the research has provided a sustainable framework for improving urban resilience. This not only reduces immediate flood risks but also ensures the long-term adaptability of urban areas to evolving environmental pressures.

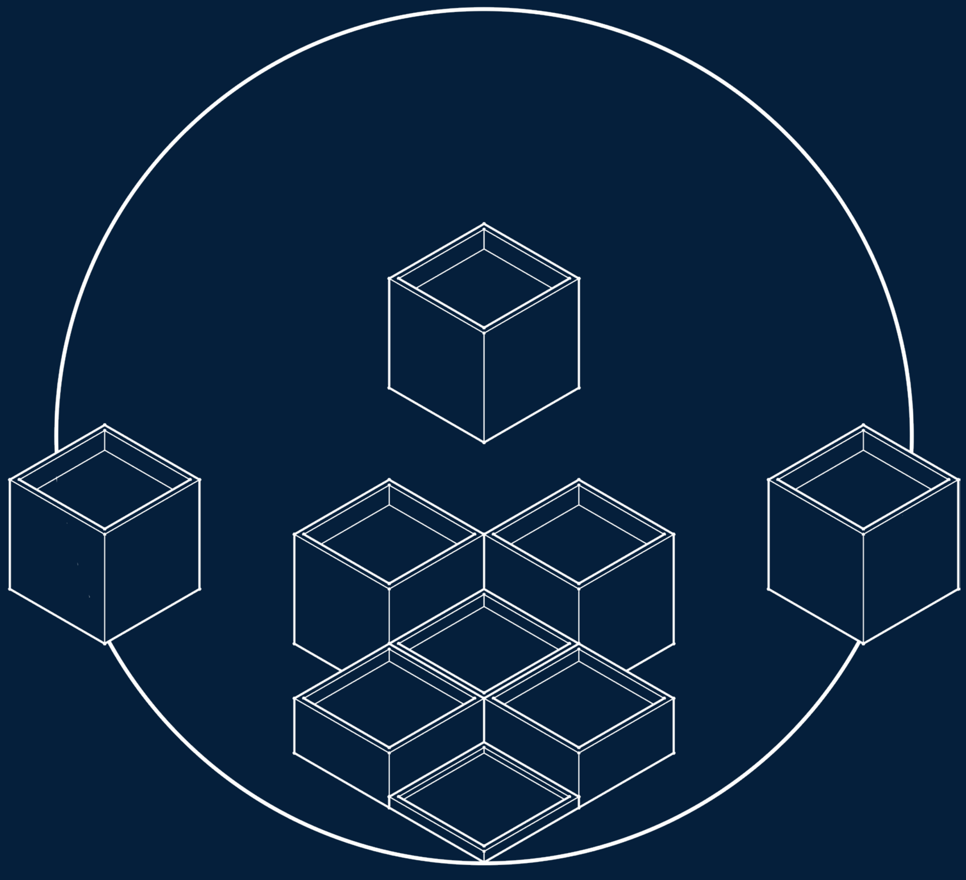
Furthermore, the integration of green infrastructure, permeable surfaces, and innovative materials has proven to be a crucial component in minimizing surface runoff and easing the burden on existing storm water systems. These strategies contribute to creating a more sustainable urban landscape that aligns with both ecological functionality and environmental responsibility.

An additional outcome of this research has been the development of a design tool, originally focused on rainwater management, which has demonstrated versatility beyond its initial scope. The tool's parametric and performance-driven capabilities allow it to be adapted for other design challenges such as energy efficiency, heat management, and urban green space optimization. This flexibility makes it a valuable asset for addressing a range of urban sustainability issues, offering designers a powerful resource for creating multifunctional, resilient urban environments.

In conclusion, this study demonstrates that by embracing advanced computational techniques and sustainability-focused approaches, urban designers and planners can create more resilient cities. The findings highlight the importance of performance-driven design in addressing rainwater management while showcasing the broader potential of the developed tool for addressing a wide array of urban design challenges. These strategies offer viable solutions for urban areas globally facing similar environmental pressures.

CHAPTER 9

REFERENCE



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