Climate Change on Singapore: Pluvial Flooding Projected Risks and Analysis

Master of Architecture Thesis Report

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Research Abstract

When what used to be 500-year floods are now occurring every 24.4 years, it becomes clear that we have entered the era of climate crisis. Increasingly extreme and unpredictable weather means we can no longer predict future weather reliably based on past data and climate patterns, and past drainage and water management infrastructure might soon become obsolete due to their inflexibility and inability to cope with longer periods of intense rainfall.

This research takes a quantitative and systematic approach to assess and manage the risks of Pluvial Floods in Singapore. This study first discusses how climate change exacerbates flooding in Singapore, as well as the importance and urgency of preparing for future floods in Singapore. Then, the Pluvial Flooding Risks Framework is introduced to identify sites that would pose high risks to human lives and the economy. Various GIS datasets are analysed to sieve out sites to prioritise for in-land flood prevention and the Marine Parade/Kembangan area is chosen as the project site for further design intervention because it poses the greatest risk to both. Subsequently, a more detailed hydrological analysis is done through Grasshopper with the Kangaroo solver to simulate existing water drainage patterns and to study how building footprint and typography affect the hydrology of the area. Lastly, this thesis examines currently available drainage solutions and suggests some suitable methods that would continue to be relevant in the age of rapid climate change.

Chapter One: Introduction

1.1. Research Background

In Singapore, flooding is often perceived as a common event that only happens in low-lying areas during heavy rainfall. A tropical city-state known for its frequent and intense downpours, mild flooding happens all the time, but most are quickly drained away by the existing network of drainage systems and creates little problems for most of the population. It is therefore easy to forget about the dangers of flooding and how much floods have impacted Singapore. Economic damages from floods were projected to have topped S$32 million between 2000 and 2015, with the floods from June to July 2010 alone costing upwards of S$23 million in tangible damages. (2019, Derrick A Paulo)

Floods and storms are among the most common and devastating natural disasters in the world, accounting for 70% of all natural disasters between 1950 and 2008 (Debarati et al. 2013) and generating enormous economic damage and fatalities globally. Floods and storm events are expected to increase in intensity, frequency and impact due to two main reasons – urban development of cities and climate change. As more cities develop, more pervious surfaces such as forested lands are converted into impervious surfaces such as roads and built areas, thus reducing the detention of water and increasing the risks of flash floods. Climate change caused by human activity, principally the combustion of coal, oil, and gas, has also resulted in a warmer, wetter, and more energetic weather environment. (Climate Council, n.d.) As a result, the hydrological cycle becomes more active, altering past weather patterns and producing more frequent and powerful rainfalls. The drastic changes in weather patterns imply that even areas of higher topography and areas with no precedent of flooding are now exposed to flood risks, and past rainfall data are becoming less useful to predict future rainfall locations and amounts, making it difficult to plan for or retrofit existing water management strategies to effectively alleviate future flood events.

Singapore is especially vulnerable to flooding due to its high precipitation and geographical location. An island city, Singapore must deal with coastal flooding caused by climate change-induced sea level rise in addition to flash floods. Low-lying coastal regions below 5m above sea level are unprepared and at risk of serious flood damage when combined with storm surges and high tides.

1.2. Scope of Study

Climate change results in an increase in the frequency and intensity of three types of flooding:

1) Coastal Flooding results from a rise in sea level due to the melting of glaciers and the thermal expansion of the sea.

2) Fluvial Flooding (River Floods) happens in downstream areas resulting from rivers and canals overflowing from increased rainfall, and

3) Pluvial Flooding (Flash Floods) results from intense downpours due to a wetter and more energetic atmosphere.

Only Pluvial Flooding would be considered for the purposes of this thesis research paper.

1.3. Research Problem

Climate change has created a more active hydrological cycle, changing past weather patterns and producing more frequent and intense rainfalls. Increasingly extreme and unpredictable weather means we can no longer predict future weather reliably based on past data and climate patterns, and past drainage and water management infrastructure might soon become obsolete due to their inflexibility and inability to cope with longer periods of intense rainfall.

1) How can we prioritise resources to prepare for floods before they occur and to alleviate flooding in areas where it is most needed?

2) How do we alleviate flooding/ reduce flood damage through different urban-scale planning strategies?

3) As we can no longer predict flood amounts in the future, how do we improve the water resilience of our cities and introduce flexibility in planning for floods?

4) What are some strategies that are currently being used to solve flooding issues?

1.4. Research Aim and Objectives

There are three goals to this thesis report.

Firstly, due to the unpredictability of the weather, we can no longer upgrade water management infrastructure based just on past flooding data. There is a need for a new framework to sieve out locations to prioritise for in-land flood prevention. In this thesis, the Pluvial Flooding Risk Framework is developed through GIS data analysis to identify sites that would pose high risks to human lives and the economy.

Secondly, there is a need to perform a more detailed hydrological analysis to find out the exact location of the problematic areas within the highest-risk site. A simulation tool is needed to evaluate different water management strategies against one another quantitatively. In this thesis, the Kangaroo solver in Grasshopper is used to simulate existing water drainage patterns and to study how building footprint and typography affect the hydrology of the area.

Lastly, this thesis examines some of the currently available drainage infrastructures and suggests some suitable methods that would continue to be relevant in the age of rapid climate change.

Chapter Two: Pluvial Flooding in Singapore

2.1. Global pluvial flooding vulnerability

Heavy precipitation increases have long been expected as a consequence of global warming. Numerous pieces of evidence, ranging from basic thermodynamic theories to simulations utilising complex coupled Earth system models, concur that the exponential growth in the atmosphere's water vapour-holding capacity would result in a significant increase in global precipitation extremes. (Trenberth et al., 2003) According to the most recent IPCC reports, a warmer atmosphere can "hold" more moisture - around 7% more each degree Celsius of warming. (Davenport 2022)
The strength of storms rises as temperatures rise, according to the IPCC's most recent assessment report. The graph depicts how much wetter major one-day storms that occur roughly every ten years are anticipated to occur as temperatures rise. (Davenport 2022)

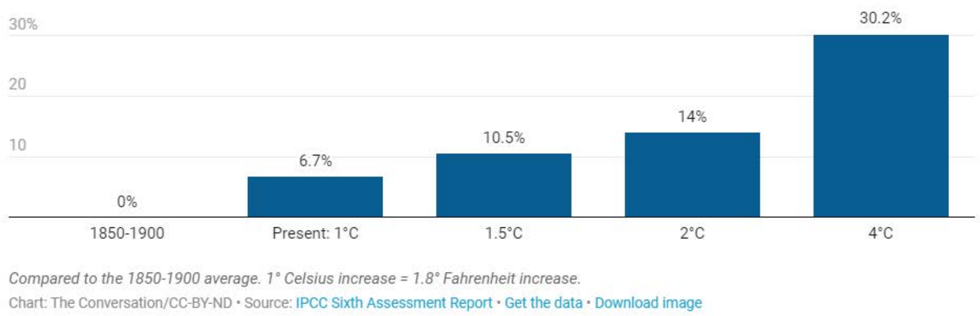


Figure 1. IPCC Sixth Assessment report on wetness per 1° Increase (Davenport 2022)

While mean global precipitation is expected to rise by 1-3% every degree centigrade of warming (Kharin et al., 2013), extreme precipitation is expected to rise by 5-10% per degree, with some locations rising even further. (Pendergrass et al., 2017).

Extreme rainfall/ precipitation event is the term used to describe brief but abnormally intense rainfall. It can be defined as "days with precipitation in the top 1 percent of all days with precipitation." (USGCRP n.d.) In the case of a high-warming scenario with rapid increases in greenhouse gas emissions, extreme rainfall events known as hundred-year storms would be expected once every 33 years. (NSF 2020) Extreme weather events are also anticipated to reduce global GDP by 5% per year by 2050 if greenhouse gas emissions continue unabated. (N. Stern 2007)

Evidence of such extreme conditions is already visible as precipitation event concentration and duration rise, resulting in pluvial floods globally. Without adaptation, the increased severity of flood risk will result in mass relocation and significant financial damage, with low-lying communities - where adaptive capacity is limited - bearing the brunt of the damage. (R.J. Nicholls, et al. 2007)

Flash Floods are the most dangerous type of pluvial floods. Flash floods occur when the volume of water collected from sudden torrential downpours cannot infiltrate the earth and the excess water flows over unplanned surfaces such as roads and buildings. As cities around the globe urbanise and develop, permeable surfaces such as forests and grasslands are converted to impermeable surfaces like roads and buildings. Infiltration rates are restricted by the existence of impermeable (low permeability) surfaces. (Barsley 2020) With more surfaces having low infiltration, pluvial flood events become more frequent and severe as grounds become easily saturated and excess water quickly overflows into unplanned channels, causing humanitarian and economic damages.

2.2 Singapore's pluvial flooding vulnerability

Because to its tropical environment, Singapore receives a lot of rain. Singapore receives 100 to 300 mm of rain every month on average, with November and December receiving the most. (Koh n.d.)The average annual rainfall is approximately 2,340 mm. (Koh n.d.)The northeast monsoon season, which affects Singapore from December to early March, corresponds with the country's wettest months. Monsoon surges, which often come in December, frequently bring significant torrential downpours, resulting in floods. (Koh n.d.)

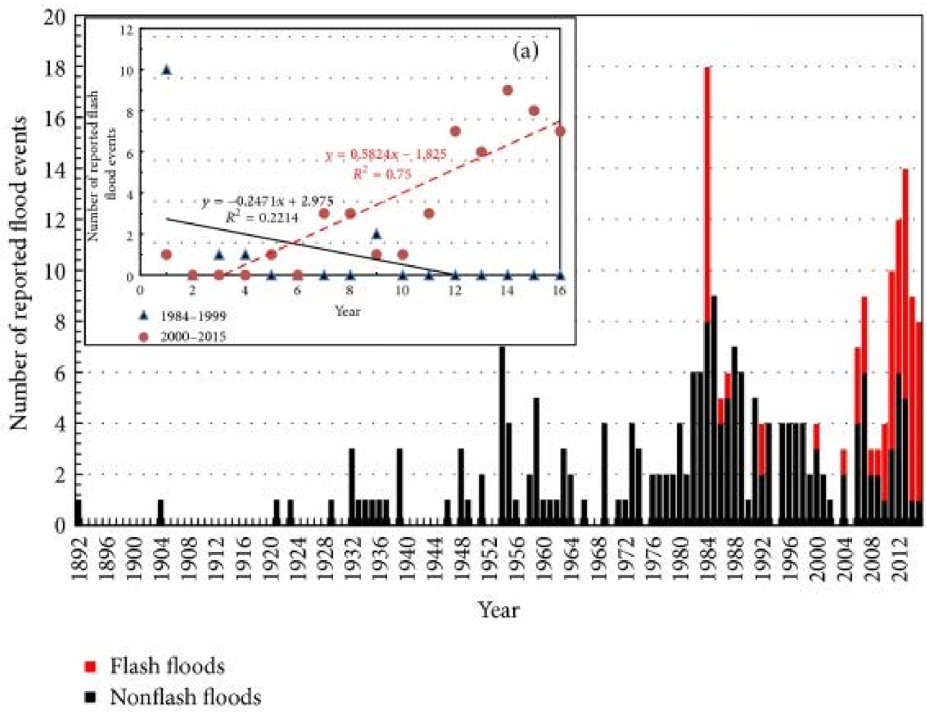


Figure 2. The frequency of overall reported Singapore floods, classified as flash floods and nonflash floods, as recorded in The Straits Times archive from 1892 to 2015. (Winston et al 2016)

Singapore's rainfall data corroborates the global rise in precipitation caused by climate change. In the data, there appears to be a noticeable and recent shift toward more flash floods in Singapore relative to nonflash floods. These findings show that flash floods, at least those with a significant impact on Singapore society and published in the local newspaper of record, are growing increasingly common in recent years. (Winston et al 2016)

There is also statistically more “Heavy Rain Days” and more intense rainfall measured in mm/hr. (Claire n.d.)

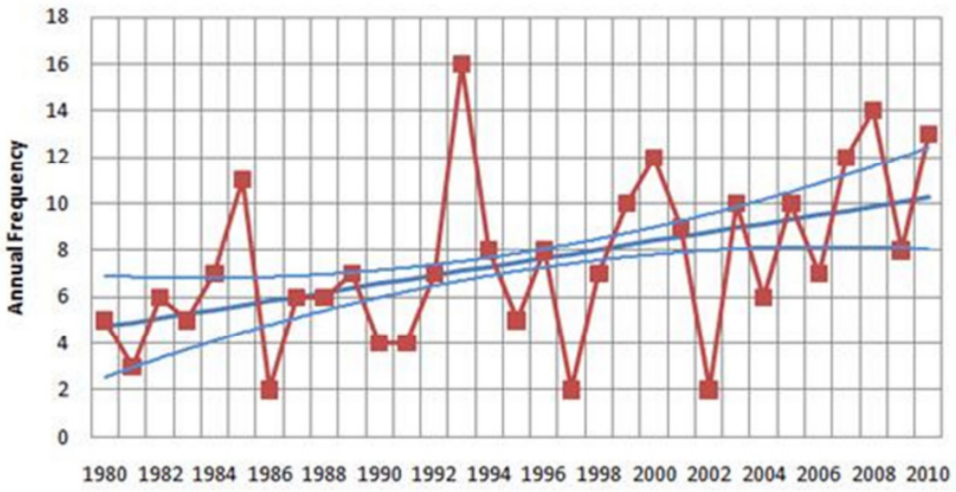


Figure 3. Annual rainfall frequency 1980 to 2010 (Claire n.d.)

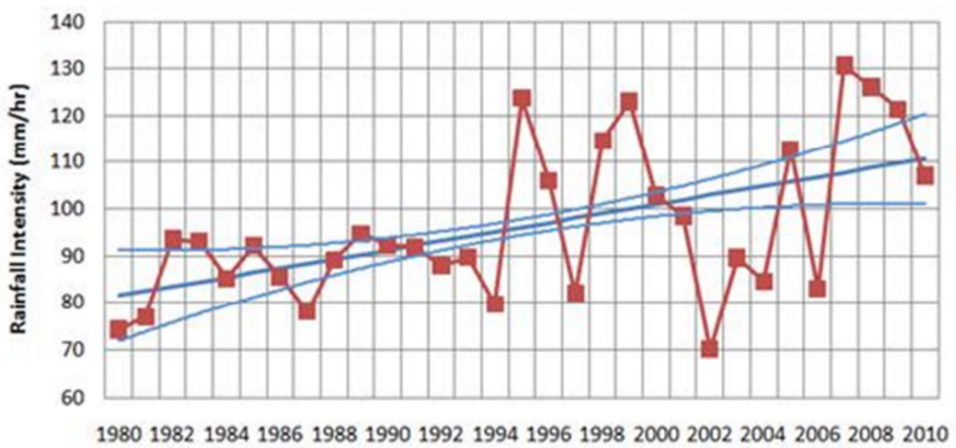


Figure 4. Historical rainfall intensity 1980 to 2010 (Claire n.d.)

Singapore’s flood vulnerability is expected to continue to increase in the future. Other than a more active atmosphere producing more precipitation and having mostly urban areas with impervious surfaces, it is the compounding effect of several adverse meteorological factors that would create the “Perfect Storm” that would have the most devastating impact and damages.

Climate change is expected to cause sea level to rise to 1m by 2100 under high carbon emission projects according to IPCC. Coupled with other factors like storm surges and and high tide, sea levels could temporarily rise to 4-5m. (The Straits Times n.d.)
A higher baseline sea level suggests more floods, as a higher mean sea level may exacerbate the effects of heavy rain or high tides. When heavy rains combine with high tides and storm surges, we will see flash floods that are more destructive than what we have seen so far. (The Straits Times n.d.)

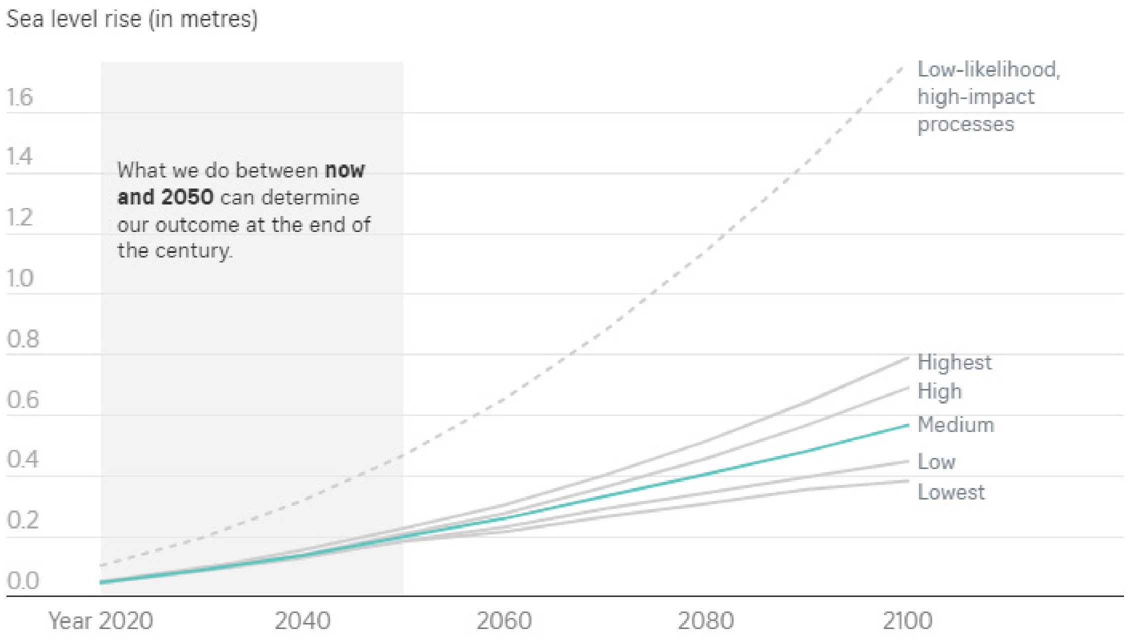


Figure 5. IPCC projections for mean sea-level rise in Singapore relative to a 1995-2014 baseline.

Figure 6. Singapore areas identified to be threatened by sea level rise

30% of Singapore's land is less than 5m above sea level, and coastal and low-lying areas are especially vulnerable to the combined effects of coastal and pluvial floods. PUB has selected four sites for intervention: along the City-East Coast stretch, Lim Chu Kang, Sungei Kadut, and around Jurong Island. (The Straits Times n.d.) However, these places are only located through coastal flooding studies. In the following chapter, we will determine places that are prone to pluvial floods.

Chapter Three: Pluvial Flooding Risk Framework

3.1. Introduction

As elaborated in the previous chapters, we can no longer predict the risk of flooding in Singapore based on past flooding data due to the unpredictability of climate change. We anticipate an increase in pluvial flooding due to the climate-induced increase in the amount of precipitation and the frequency of torrential pours. But with no reliable past data to rely on and to extrapolate and predict future rainfall patterns, we cannot predict where and when these rainfall events would happen. There is now a need to develop a new method to assess the risk of pluvial flooding in areas all around Singapore.

The Probabilistic approach is the conventional method of calculating flood risk. It is based on probability theory and regards hazard estimation as the estimation of the likelihood of occurrence of a specific natural event with an estimated frequency within a specified period of time (Pistrika and Tsakiris 2007). The probabilistic approach assumes that occurrences in the future are predictable based on past experience. 2007 (Pistrika and Tsakiris)

While this method was useful to extrapolate significant flood volume for water strategies planning before the climate change era, such as estimating 100-year floods and 500-year floods, this method was not useful to pinpoint the exact locations of the flood events. This is due to the constant changes in the many factors that are present in the atmosphere, such as temperature, air pressure, cloud patterns, precipitation, and wind factors including its speed, direction, and moisture level; all of which affects weather patterns and changes the location affected by rain. (Warrilow n.d.) In fact, while a 5–7-day weather forecast can be about 80% accurate, its accuracy drops to 50% when predicting weather patterns for 10 days or longer. (Huttner 2020) Combined with climate change induced variations, which give rise to 500-year flood events happening within the span of just a few years, it is almost impossible to accurately predict weather patterns and rainfall events 10, 20 years down the road. Planning water management strategies base on this approach could mean overplanning and erecting infrastructures for areas that might receive little rainfall in the future, and under planning for areas that would be in dire need of flood management.

In light of this, I propose a framework that is less targeted on weather patterns, and more focused on the geographical flood vulnerability/ the risk of flooding of each area in Singapore. This framework first divides Singapore into smaller areas based on their topological watershed (drain basin grids), and then uses criteria such as built density (Building Footprint), Types of landuse, existing areas vulnerable to flooding (PUB list of flood-prone areas and hotspots), and areas that are recently and sufficiently dealt with (ABC water management sites) to calculate the flood risk score and assess the flood vulnerability of the area. This method uses existing Geographical Information System (GIS) data from the Singapore government and the global digital elevation model (DEM) to provide a detailed analysis at a relatively high resolution.

3.2. Methodology

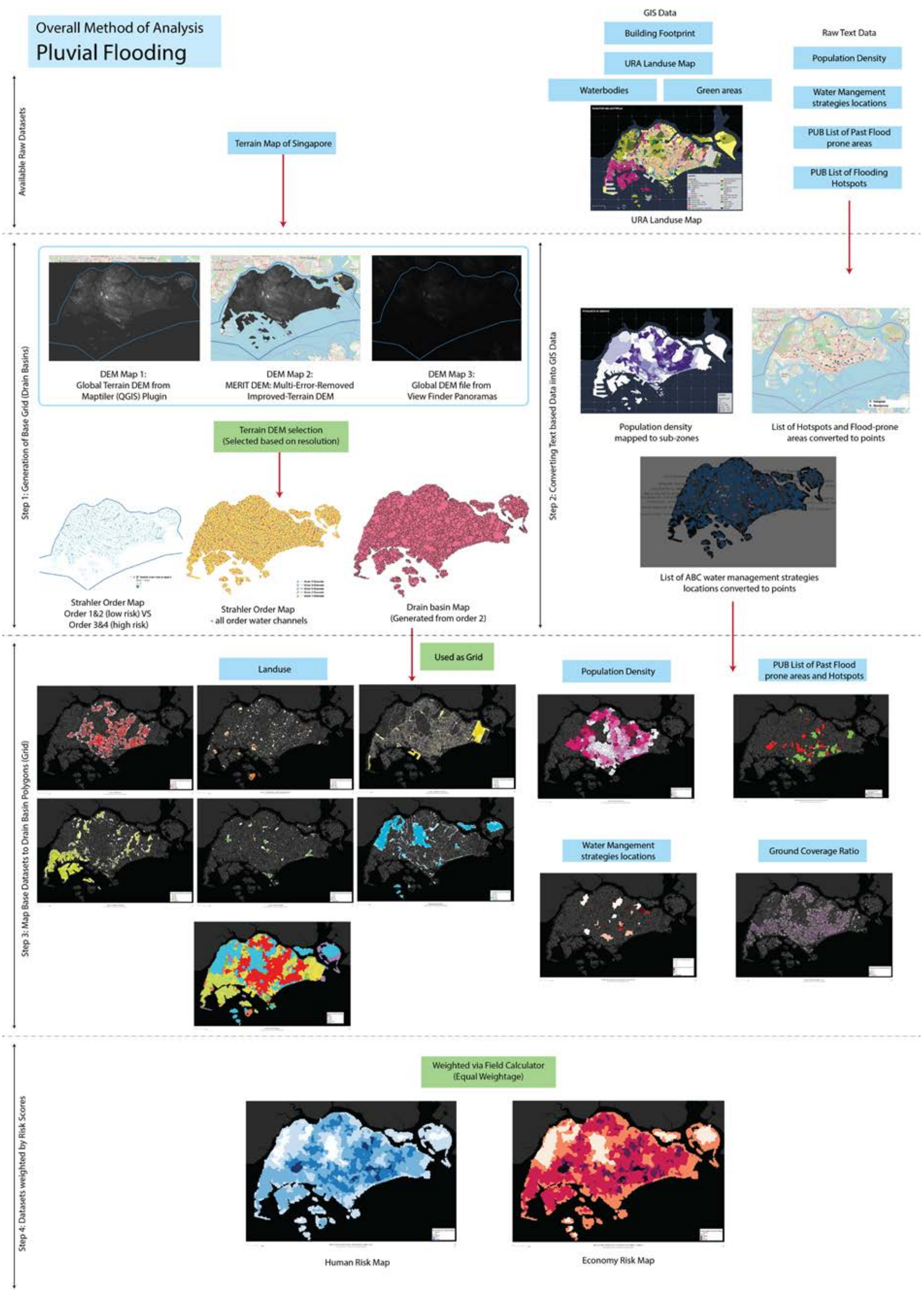


Figure 7. Overall Method of analysis: Pluvial Flooding

The pluvial flooding framework can be divided into 4 parts.
i) Generation of the base grid (Drain Basin)
ii) Converting all data into GIS compatible data and Map datasets to grid for comparison
iii) Weigh datasets by Risk Scores

I. Generation of the base grid (Drain Basin)

The drain basin grids are generated from a watershed analysis of the digital elevation model (DEM) of Singapore. The DEM reflects the topology of the Singapore terrain through a range of grey tone values. With this DEM, we can generate the Drain Basins as a base grid and generate the Strahler order map.

Goal:
From Topography map, to look for areas with Higher Speed and Intensity of Flooding based on topography and create a grid system to evaluate flooding (drain basins).
Higher Strahler Order >> Higher Speed and Intensity of Flooding (due to more streams of water)
Drain Basins >> area of ponding according to the Strahler order

Method of Analysis:
Select sufficiently high-resolution terrain DEM >> Watershed analysis >> Strahler Order Map and Drain Basins generated

Step 1 - Choosing a High-resolution DEM terrain map of Singapore

There are currently very few high-resolution DEM terrain maps that are publicly available. However, since the generation of the Drain basins forms the foundation of the whole Pluvial Flooding analysis method and it is generated from the DEM raster file, it is very important to compare available resources and choose the highest resolution DEM to base our analysis on.
I have analysed 3 different DEM maps.

1. Global Terrain DEM from Maptiler (QGIS) Plugin
2. MERIT DEM: Multi-Error-Removed Improved-Terrain DEM from Tokyo University
3. DEM file from View Finder Panoramas

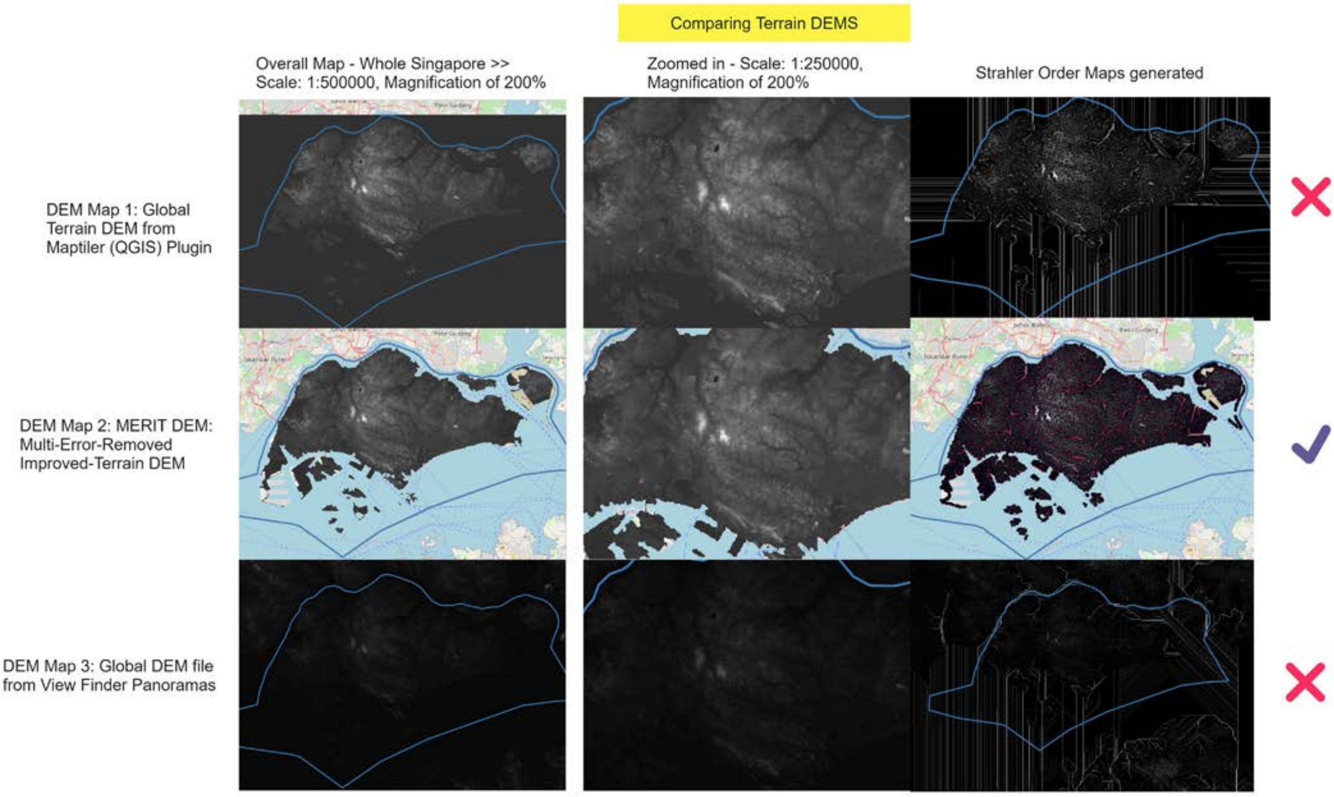
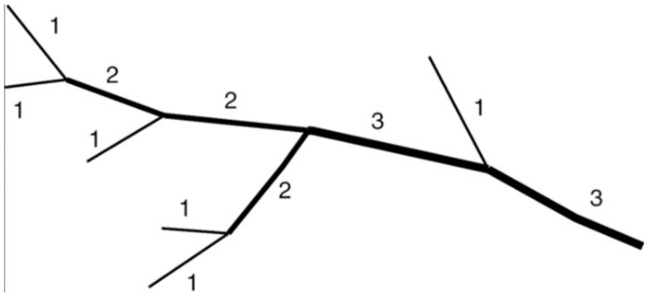


Figure 8. Overall Method of analysis: Pluvial Flooding

After the comparative analysis, DEM Map 2 is Selected for the purpose of the Watershed Analysis.
Resolution of DEM Map 1 and 2 are comparable, DEM Map 3 has been eliminated due to lower resolution/ image being too dark. Out of DEM map 1 and 2, DEM Map 2 has higher contrast. And due to the development process of DEM Map 2 taking 3 other DEM Maps as reference, it can be assumed that DEM Map 2 has a higher accuracy. This is supported by the quality of the Strahler order maps generated too. With Map 2 generating the one with the highest quality.
All in all, while DEM Map 2 lacks data for some of the reclaimed areas, it seemed to the highest resolution out of the 3, sufficient to do flooding analysis for mainland Singapore.

Step 2 – Generating Strahler Order Map

Strahler Order indicates how streams of water would flow based on the difference in terrain.



According to the system made by Strahler, rivers of the first order are the outermost tributaries. If two streams of the same order meet, the resulting stream is given a number that is one higher. If two rivers of different stream orders meet, the resulting stream gets the higher of the two numbers. (Strahler 1957)

This can be used to determine the intensity of flooding as higher Strahler Order would mean more streams of water (from different directions) meet, thus resulting in quicker and more intense flooding. In this Strahler Order mapping of Singapore, 5 orders have been identified. The lighter the colour, the higher intensity and speed flooding would occur in the area.

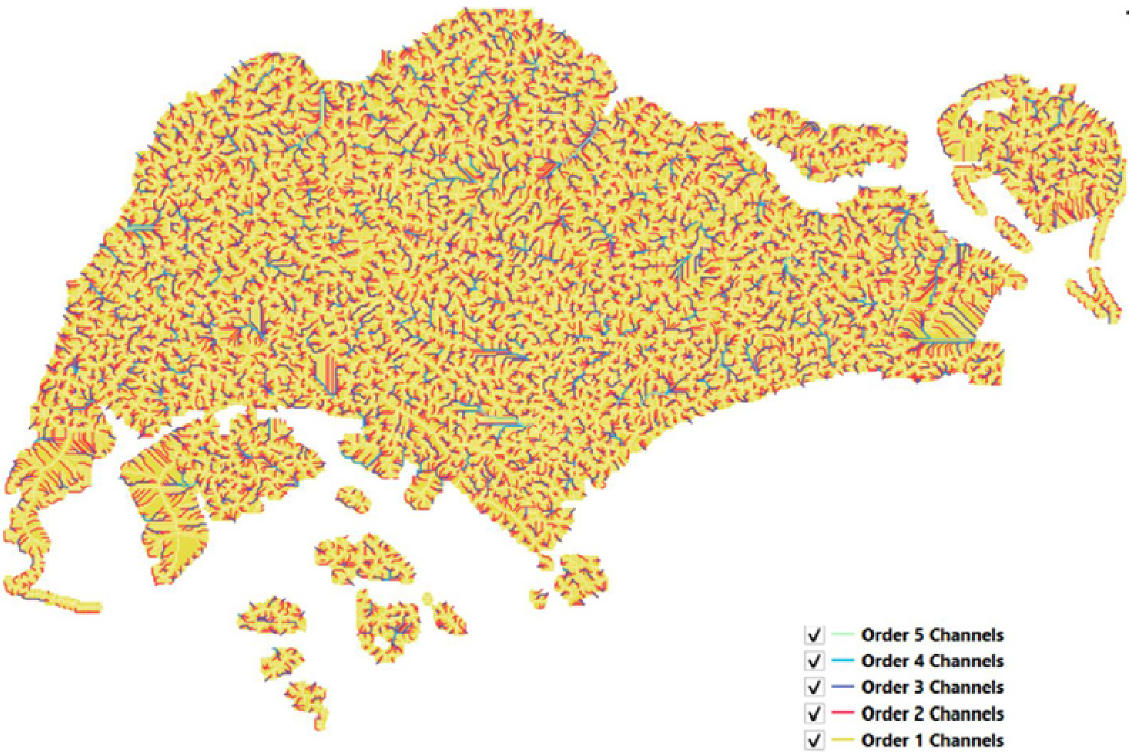


Figure 9. Strahler Order Map of Singapore

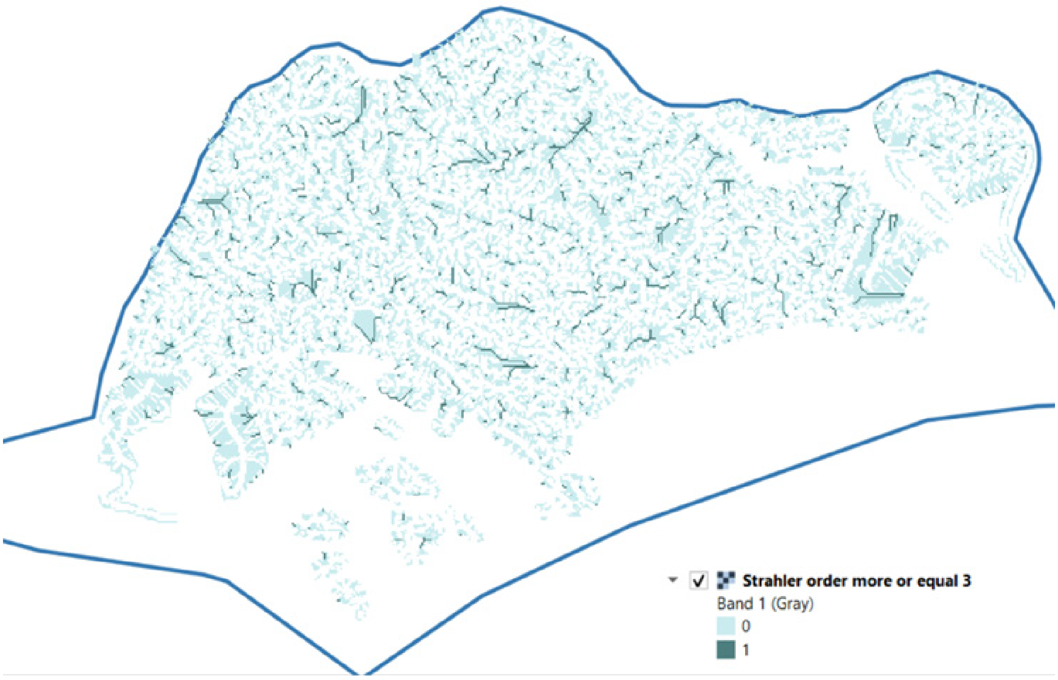


Figure 10. Strahler Order Map classified by risk

“High Risk areas” shown in Dark blue (Strahler order more or equal 3) - Rainwater can be retained by vegetations
“Low Risk areas” shown in Light blue (Strahler order 1 and 2) - Rainwater has to be managed by grey/ hybrid infrastructure

Step 3 – Generation and selection of Drainage Basin (DB) Grid from Watershed analysis

The Watershed analysis is also generated from the terrain DEM. It studies topological differences and generate points when it senses a change in the water channelling direction. From these points, continuous polygons are then formed, they represent the natural terrain's ponding areas. (Drainage basins)

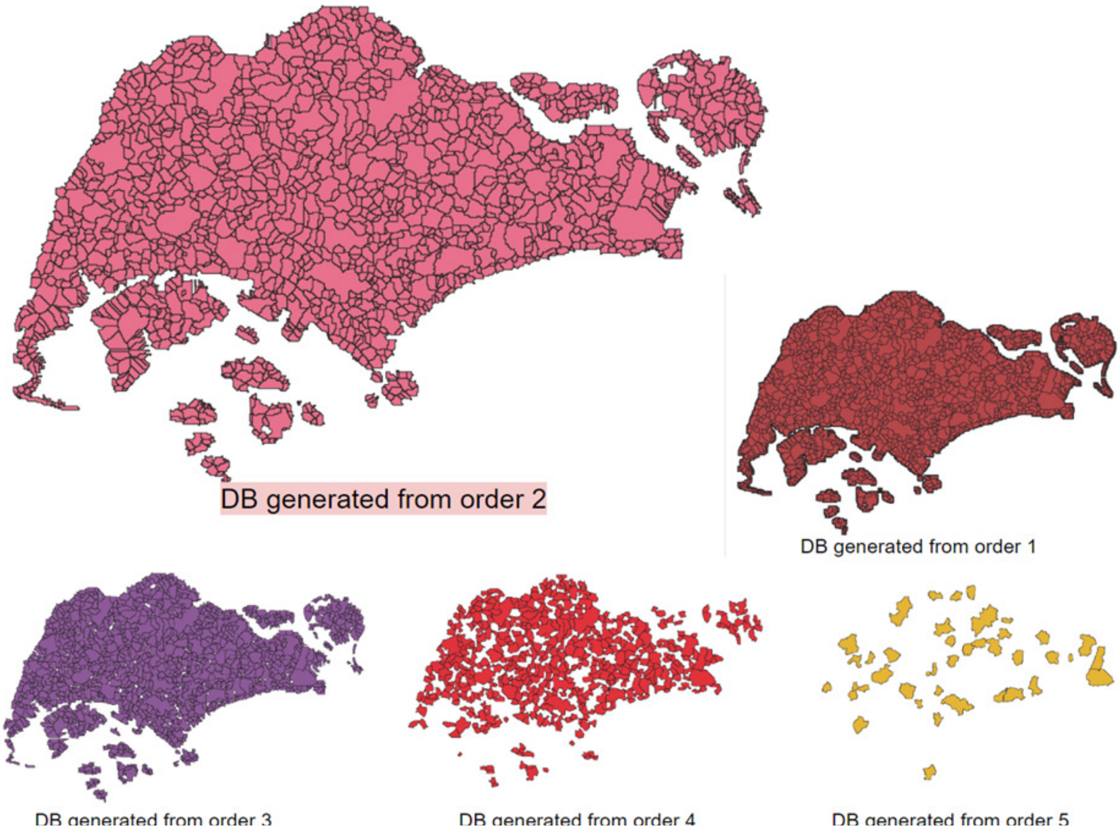
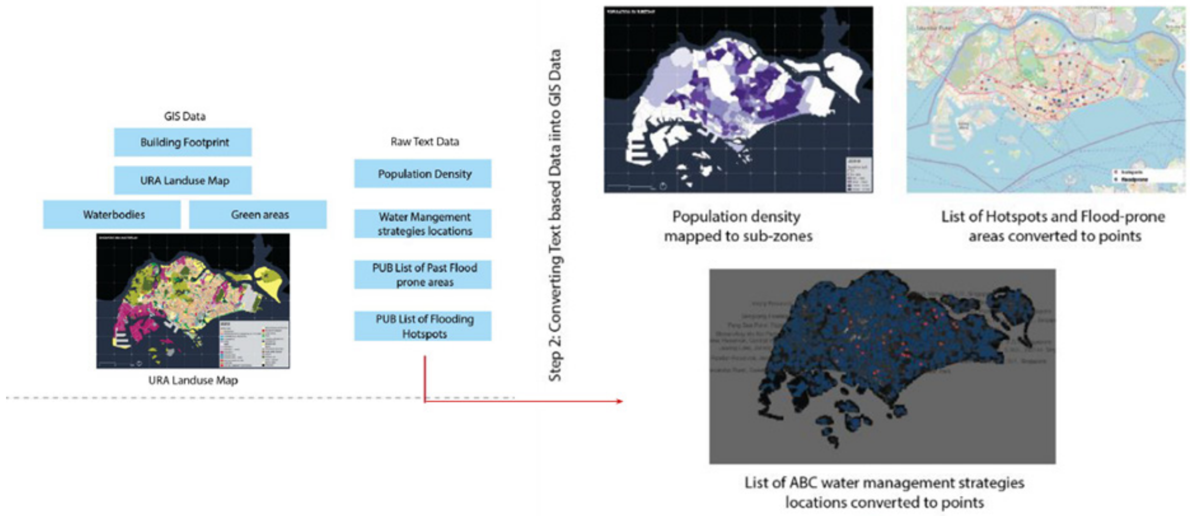


Figure 11. Drainage basins order 1-5

For the selection, different order drain basins are compared. Since there are 5 Strahler orders, 5 types of drainage basin grids can be generated.

DB generated from order 2 is selected as the overall grid. Order 3, 4, and 5 are not selected as they generate drain basin grids only for some areas and omitting other, which would create an incomplete analysis that does not consider all parts of Singapore. Order 1 is not selected as there were additional geometries created that are too small for analysis while overlapping other bigger polygons, which might contribute to an inaccurate analysis.

ii) Converting all data into GIS compatible data and Map datasets to grid for comparison



ii) Converting all data into GIS compatible data and Map datasets to grid for comparison

Goal:
Map different datasets such as land use, population density, green map, water management location, hotspot to the drain basin polygons as percentages so that each polygon can be compared easily.

Method of Analysis:
1) Land use:
- Land use Type (Residential/ Industrial etc)
  Assess the extent of economic and humanitarian damaged in each DB polygon area.
- Green and Blue spaces
  Higher % area, lower risk of flooding

2) Population Density: Assess the no. of people affected in each DB polygon.

3) PUB list of Flood prone areas and Hotspots: Assess the existing risk of flooding in each polygon

4) ABC water management locations and methods: Areas that have been adequately dealt with by updated and sustainable water management measures.

5) GCR (Ground Coverage Ratio): Higher GCR, higher built ratio, higher risk of flooding

These datasets are prepared so that they would be compatible for weighting, based on this equation:
"Land use Risk" - " Blue and Green Risk" +"Population Density" - "ABC Risk" + "Flood prone" +"Hotspots" + "GCR Risk"

Step 1: Landuse Maps – Grouping Landuse into classes based on risks to human lives

After all the land use areas has been mapped in each DB polygon, classes are then assigned each of them according to the damages and risk they would post to human lives. After that, these are mapped back onto the DB grid to reflect the types of risks each DB polygon is exposed to.

(Class 1) Highest Risk - Residential buildings

Residential with commercial 1st storey (Shophouses) + Residential + Residential/ Institution

(Class 2) High Risk - Humanitarian + Other Essential Facilities

Civic & Community Institution + Health & Medical Care + Utility + Educational institutes

(Class 3) Medium Risk - Transport Facilities

Road + Transport Facilities + Rapid Transit + Port/Airport

(Class 4) Low risk to human lifes, High economic damages - Economic Facilities

Commercial & Residential (shopping mall + condo) + Commercial

Business Park + Business Park - White

Business 1 (B1) + Business 1 - White + Business 2 (B2) + Business 2 - White

+ Agriculture + Hotel

(Class 5) Lowest Risk - Social Facilities

Cultural and heritage, Religious (cemetery, Place of worship), Leisure and Entertainment, Sports and Recreation, Beach area

(Reserve Sites, Special Uses and White Sites not included)

(Parks, Open Spaces and Waterbodies mapped under Green and Blue spaces)

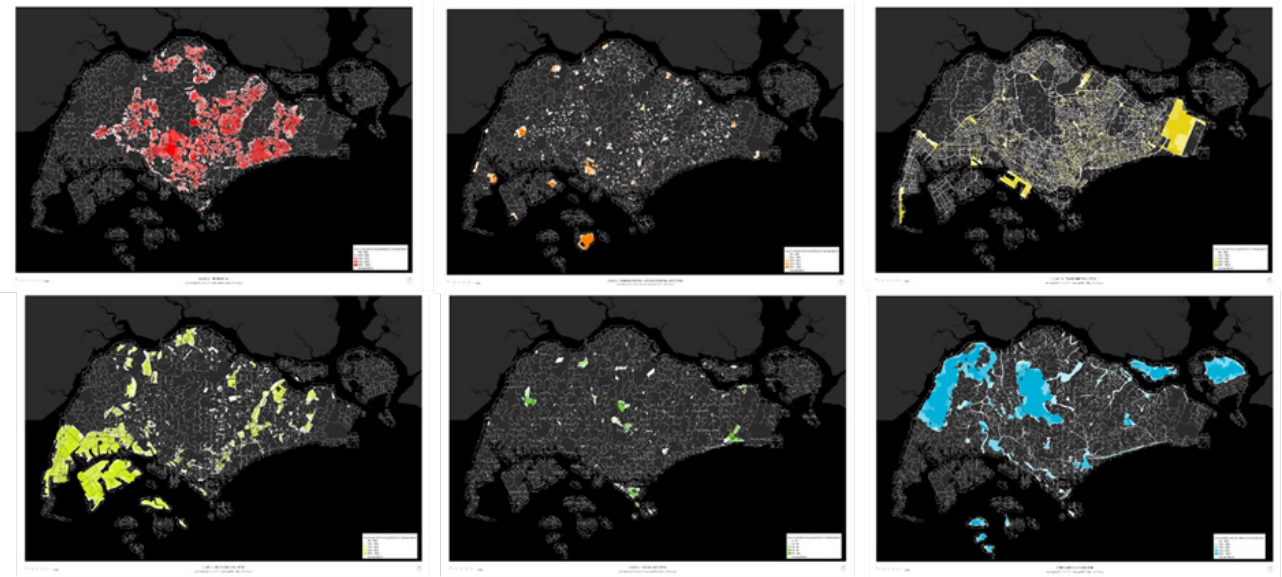


Figure 12. Mapping of class 1 – 5 and Blue Green areas

Step 2: Population Density Map

Created by an intersection of existing text-based population density by subzone dataset with the drainage basin grid, expressed as percentages.

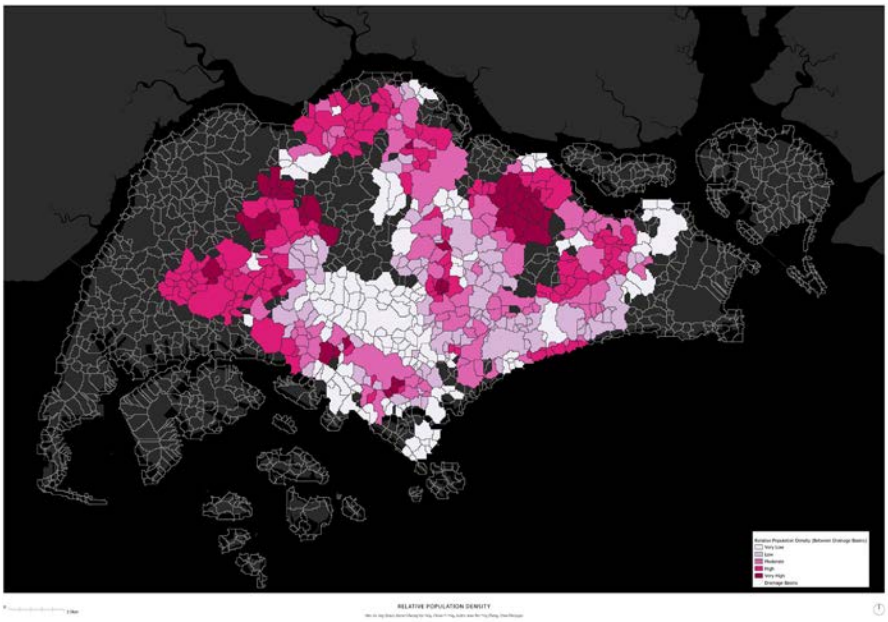


Figure 13. population density map

Step 3: PUB list of Flood Prone areas and Hotspots mapped to DB grid

PUB has published a list of areas that are historically known to be flood prone and hot spots for surface water floods. (PUB n.d.) These lists can be found in the Annex.

Geocoding plug-in in QGIS is used to locate the locations of these areas and map them onto the corresponding DB polygons.

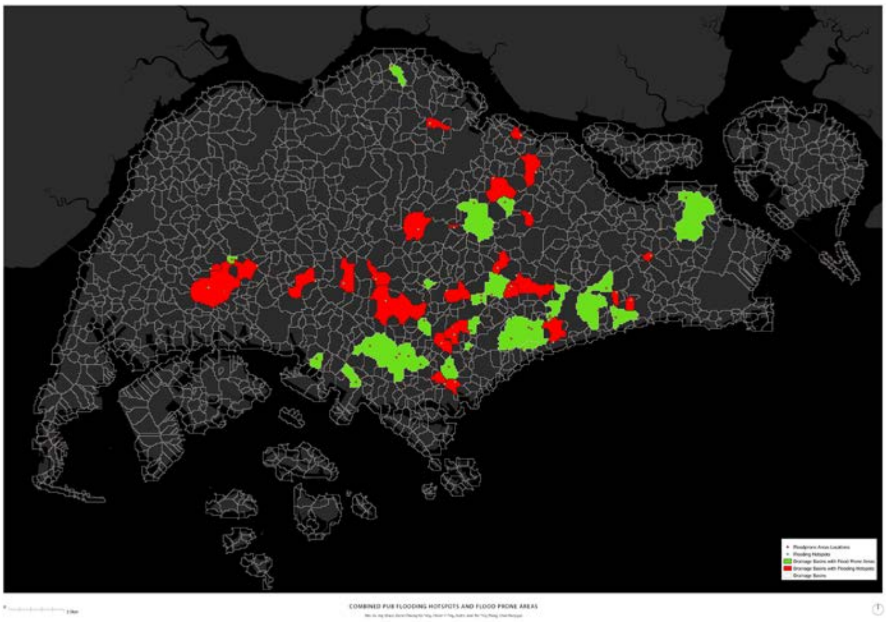


Figure 14. PUB list of Flood Prone areas and Hotspots map

Step 4: Existing ABC Water Management Mapped to DB Grid

The locations of the ABC water strategy found in PUB (PUB n.d.) are first geolocated in QGIS and intersected with the DB grids to find out which DB contains these strategies. After that these strategies are compared against one another to assess how effective they are by considering the number of ABC strategies present in each ABC sites, and the reduction of peak rainwater runoff of each strategy.

Table 3. Peak flow reduction performance of the various feature types for the 10-year design storm.

Design Feature Type	Average Peak Flow Reduction (%)	Average Normalised Peak Flow Reduction (%)
Rain gardens *	39%	47%
Gravel swales	9%	25%
Vegetated swales	0%	0%

Note: * Excluding rain gardens without orifice outlets (i.e., rain gardens FB6, FB10, FB15 and FB17).

Figure 15. Effectiveness of different types of ABC strategies compared to one another (Wing Ken et al.

Type of strategy	Strategy Effectiveness	Strategy Effectiveness Class Ratings
Parks and reservoir	Very High	5
Canals	High	4
Rain Gardens	Moderate	3
Gravel Swales	Low	2
Vegetated Swales	Very Low	1

Figure 16. ABC strategies grading system

*ABC sites that include 'Parks and reservoir' strategy are removed from the assessment as any successive strategies included will have minimal contribution to ABC strategy effectiveness

A score is given to each of the ABC sites based on their percentage effectiveness in reducing water run off/ retaining water.

10% - 5 , 30% - 4 , 40% - 3, 50% - 2, 70% - 7, 90% - 1

("Canal" * 4 + "Rain Garden" * 3 + "Bioretention" * 2 + "Gravel Swale") / 2

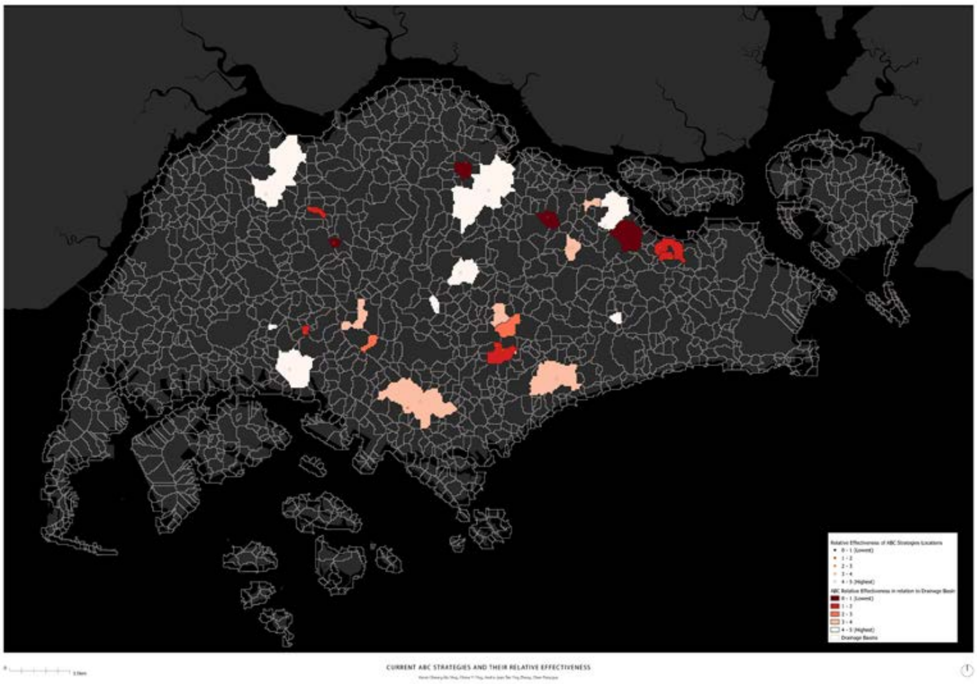


Figure 16. Existing ABC Water Management Map

Step 5: GCR (Ground Coverage Ratio)

The GCR map is created by mapping building footprint to each DB polygon, getting a total of all the areas and then dividing the total building footprint area by the area of the DB polygons.

GCR % = (building footprint area "FP area"/ Grid area "DB area") * 100

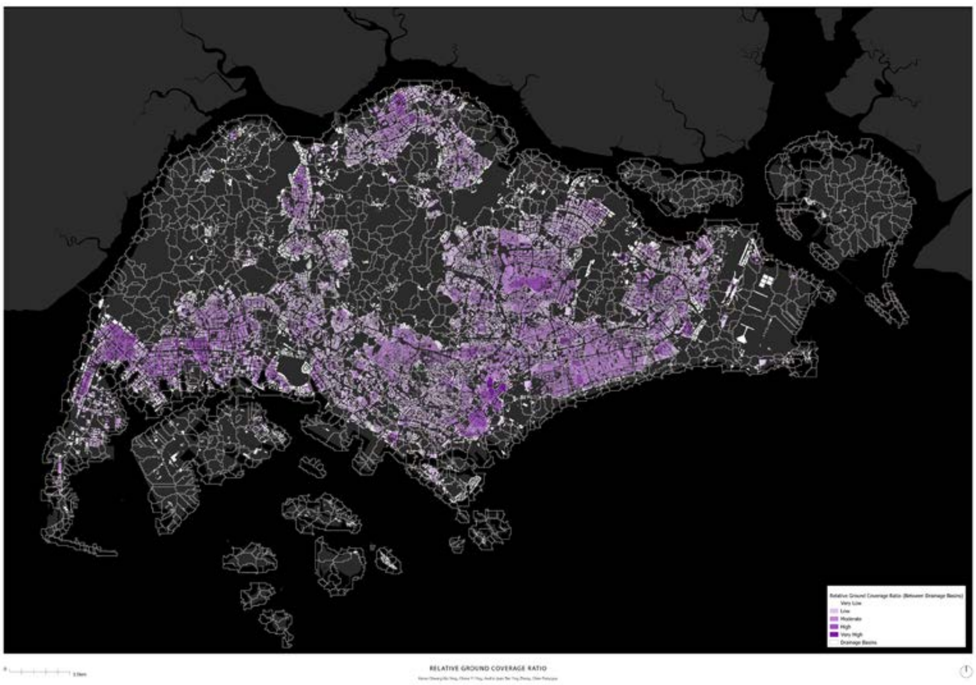


Figure 17. PUB list of Flood Prone areas and Hotspots map

iii) Weigh datasets by Risk Scores

After inputting all data sets into QGIS and mapping them to a common base of the DB polygon grid, each DB polygon has attributes that can be compared with others to assess their flood vulnerability when compared with other DB polygons. However, due to the large variety of datasets involved, some have different base values which would make the comparison process problematic (some are percentages with a base of 100, while some are scores with a base of 5). Each dataset is therefore re-classified to a base of 5.

- Green and Water areas (-ve risk)

Values in % reclassified out of 5

("Green n Bl" / 100) * 5

- GCR% (+ve risk)

Values in % reclassified out of 5

("GCR%" / maximum ("GCR%")) * 5

- ABC (-ve risk)

Calculated as "ABC Risk" previously

- Population Density (+ve risk)

Values reclassified out of 5

("density" / maximum("density"))* 5

- Flood prone and hotspots (+ve risk)

present >> 5, NULL >> 0

The landuse classes can be used to assess 2 types of risks – Impact on Human Lives and Impact on Economy.

1) Land Use - Impact on Human Lives (+ve risk)

Risk Causative Criterion	Unit	Class	Risk Class Ranges and Ratings	Risk Class Ratings	Weight (%)
Land Use - Impact on Human Lives	Classification	Class 1 (Residential)	Very High	5	
		Class 2 (Humanitarian and other Essential Facilities)	High	4	
		Class 3 (Transport facilities)	Moderate	3	
		Class 4 (Economic facilities)	Low	2	
		Class 5 (Social)	Very Low	1	

2) Land Use - Impact on Economy (+ve risk)

Land Use - Impact on Economy	Classification	Class 4 (Economic facilities)	Very High	5	
		Class 3 (Transport facilities)	High	4	
		Class 2 (Humanitarian and other Essential Facilities)	Moderate	3	
		Class 1 (Residential)	Low	2	
		Class 5 (Social)	Very Low	1	

Two maps are generated as a result, with each criteria having the same weightage.

"Human Risk" Map

"Land use Human Risk" - "Land use Blue And Green" - "ABC Risk" + "GCR Risk" + "Flood prone" + "Hotspots" + "Population Density"

"Econs Risk" Map

"Land use Econs Risk" - "Land use Blue And Green" - "ABC Risk" + "GCR Risk" + "Flood prone" + "Hotspots" + "Population Density"

3.3. Results

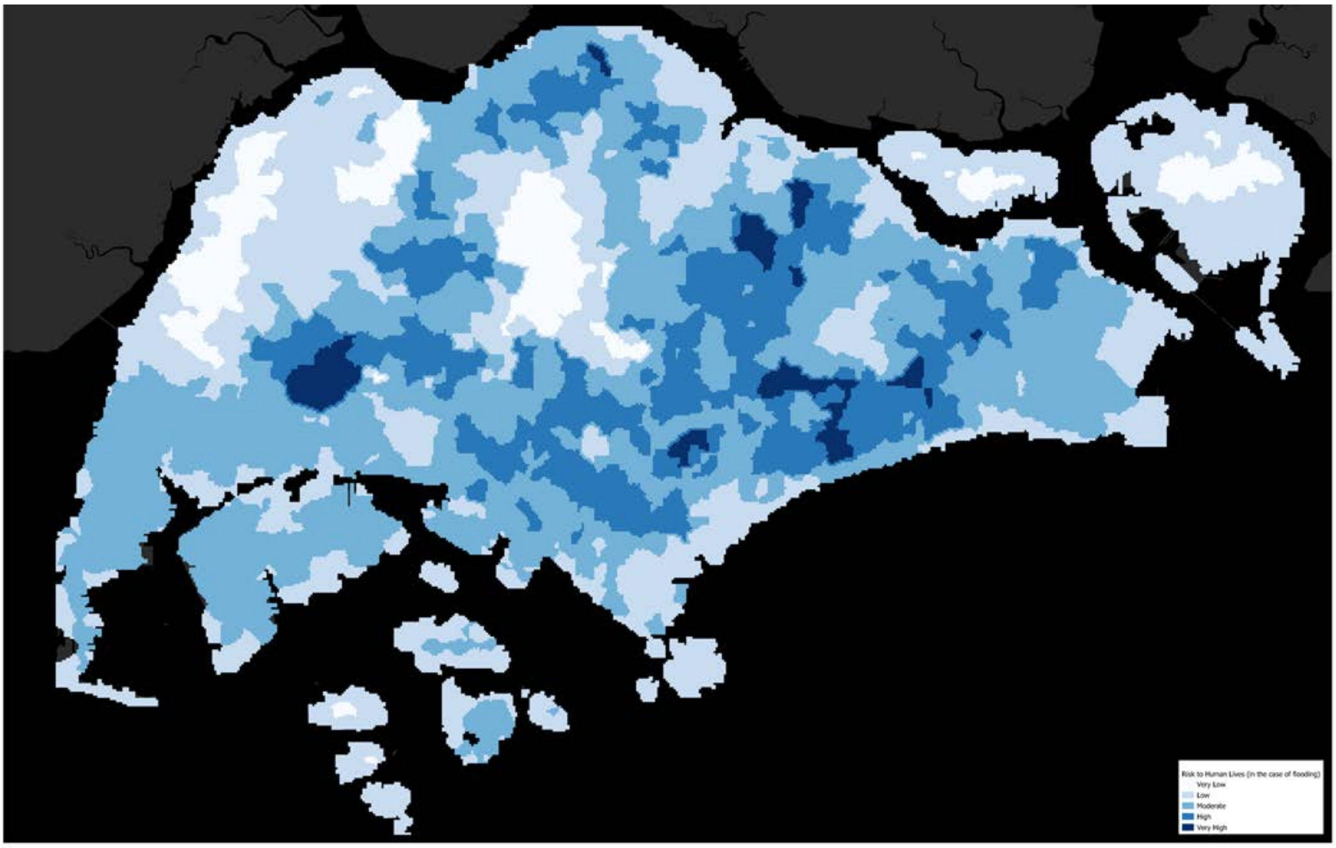


Figure 18. Flood Risk to Human Lives Map

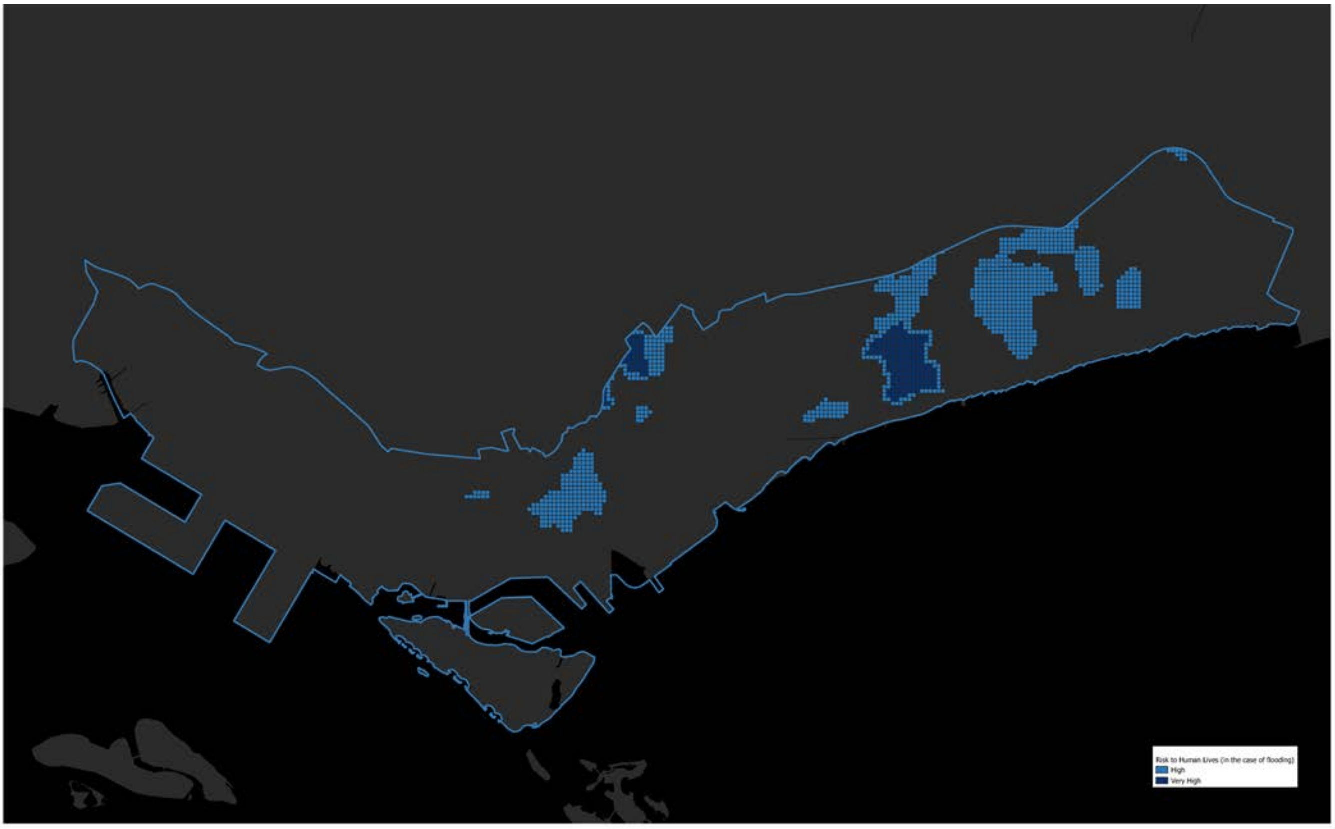


Figure 19. Critical Areas within site boundary (Human risks)

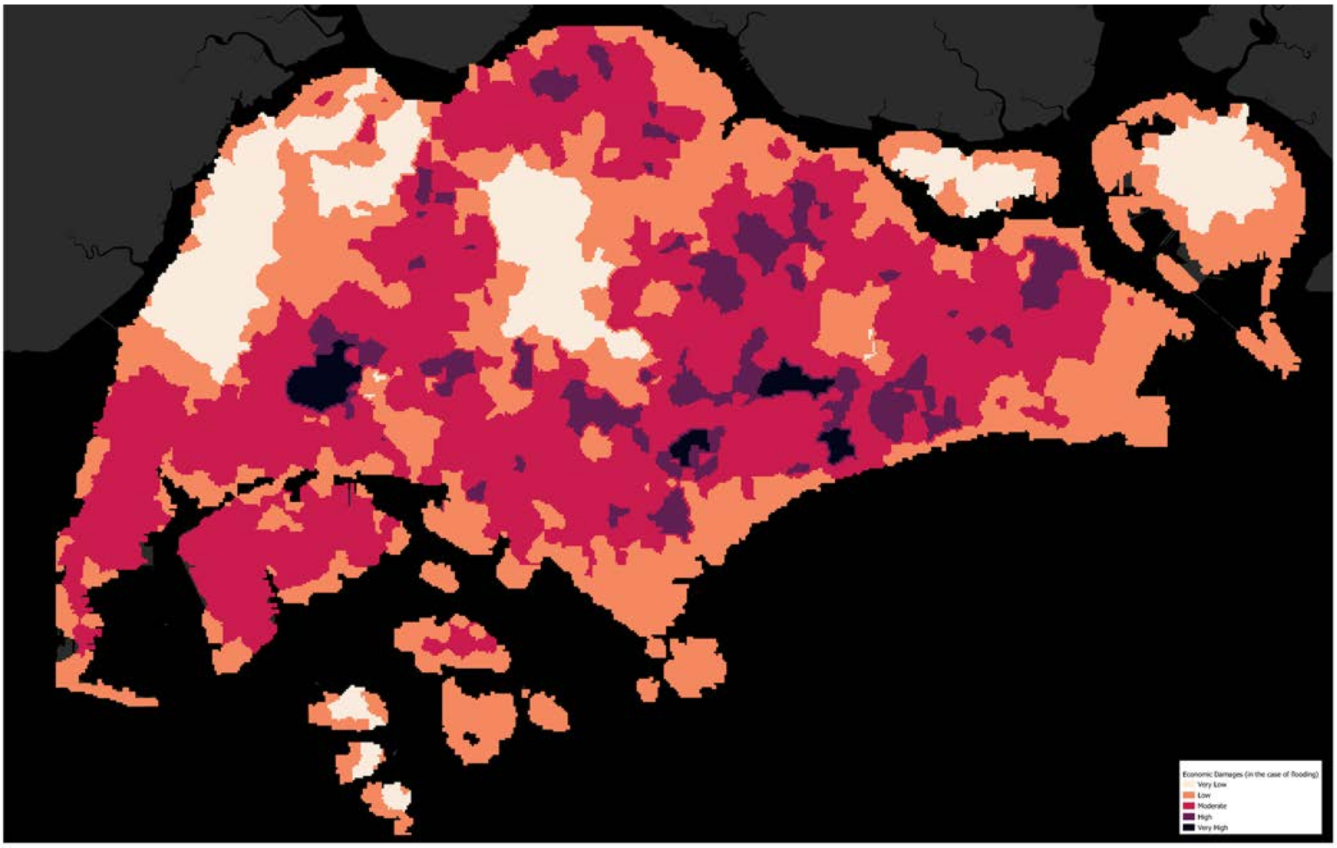


Figure 20. Flood Risk to Economy Map

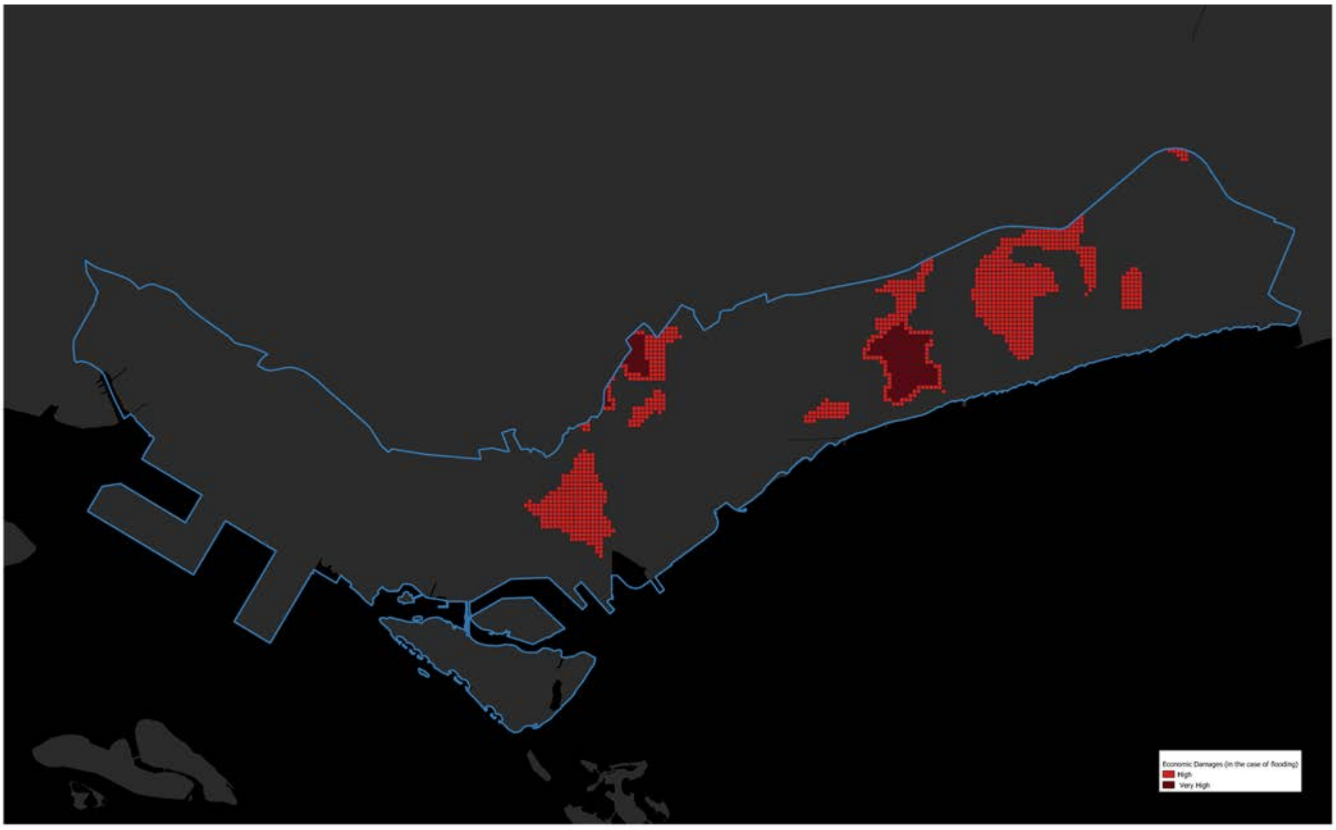


Figure 21. Critical Areas within site boundary (Economic risks)

3.4. Discussion and limitations

From the results of the analysis, we can see that there are a few areas that are especially vulnerable to the impacts of pluvial flooding, namely, the Marine parade/ Kembangan area, Bedok, Rocher, and Tanjong Pagar/ Chinatown area. This suggests that the government could invest more in drainage infrastructures in these areas/ upgrade the drainage infrastructures in these areas first due to the potential devastating impacts it would have for the country if these areas flood heavily.

However, the accuracy of this framework's results depends heavily on the quality and resolution of datasets used as inputs. Many of the datasets used in this study are not completely accurate. For example, the MERIT DEM terrain map that is the backbone of this study is still quite low resolution despite being the most accurate DEM available publicly. Moreover, building footprint data is generated from Open Street Map that is based on a shadow analysis of satellite images and area thus prone to errors as well. Despite these inaccuracies in the current studies, they are relatively easy to eliminate in the future by replacing the current datasets used in the framework with more accurate ones when they become available.

However, the accuracy of this framework's results depends heavily on the quality and the types of datasets that are deemed as relevant and used as inputs.

Right now, only criteria such as built density (Building Footprint), Types of landuse, existing areas vulnerable to flooding (PUB list of flood-prone areas and hotspots), and areas that are recently and sufficiently dealt with (ABC water management sites) are deemed as useful for assessing flood vulnerability of an area. Many more factors such as Drainage capacity of existing drainage infrastructure, soil type and age of buildings can also affect the vulnerability of an area to flooding. While these datasets are not currently considered in the Pluvial Flooding Analysis due to the considerable difficulty to obtain these data, these datasets can be simply added onto the framework as an additional "Layer" when the need arise or when these information become readily available. As more and more datasets are used as input, the accuracy and reliability of the result should increase.

Chapter Four: Waterflow Analysis and Simulation

4.1. Introduction

I have chosen the Marine Parade/ Kembangan area to be my site of intervention, as it has some of the highest risks scores for both Human Lives Risks and Economic Risks. Moreover, this area is close to the coastline and has been labelled as one of the areas that is most vulnerable to coastal flooding. The combination of high vulnerability to both pluvial flooding and coastal flooding makes this area the most in need of innovative water management strategies to alleviate flood issues. The site boundary is defined by its watershed drainage basin.

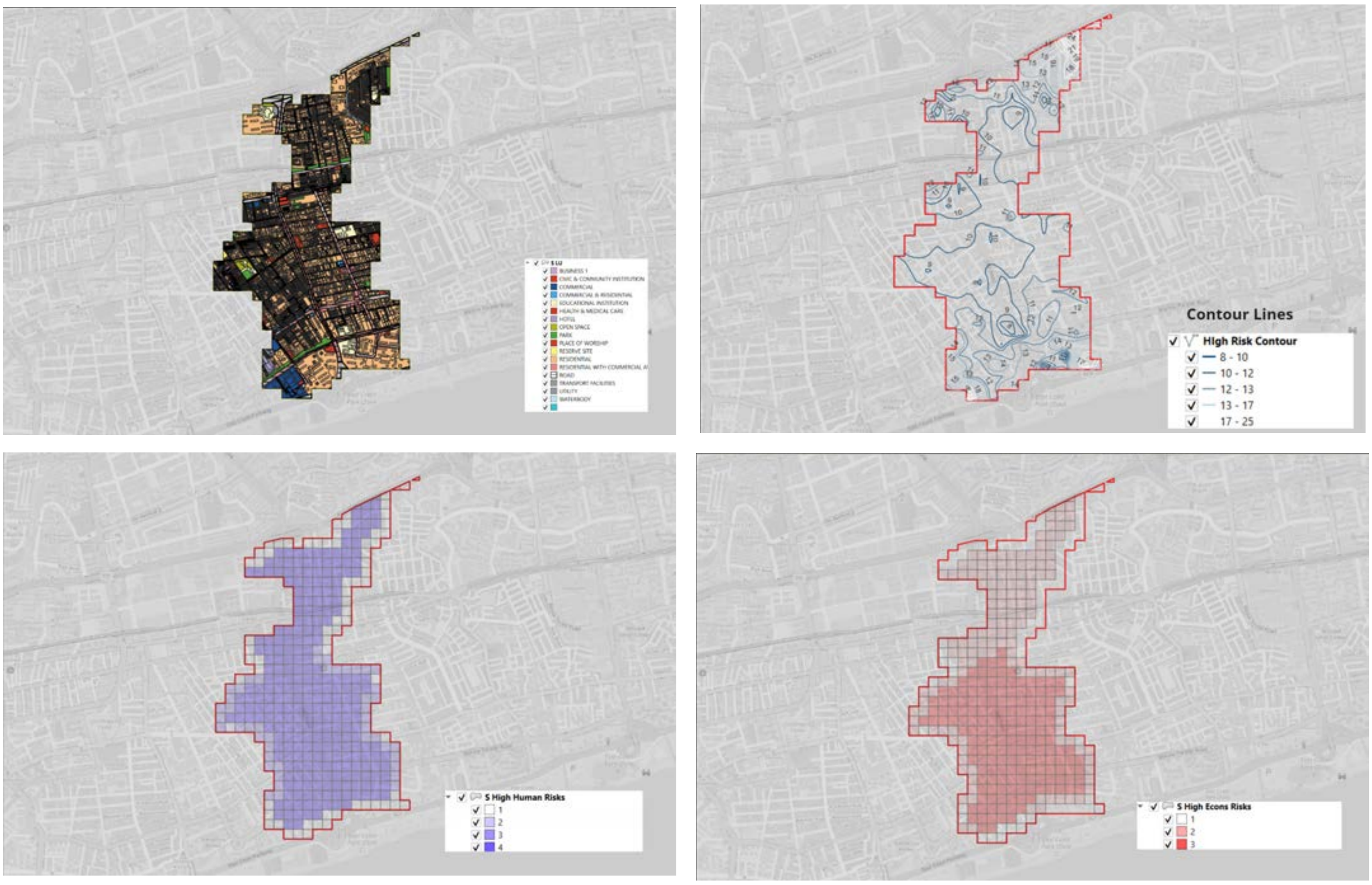


Figure 22. Site GIS data maps

A detailed hydrological analysis following the SRTF method (Morschek et al. 2019) is then conducted to find out the exact location of the problematic areas within the highest-risk site. The Kangaroo Solver in Rhino Grasshopper is a physics engine that can simulate gravity pull and particle collision. The Step Solver function also allows water flow lines to be tracked, allowing for analysis of each individual particle flow. This tool would be useful in evaluating different water management strategies against one another quantitatively, and to study how building footprint and typography affect the hydrology of the area.

4.2. Methodology

To improve flood resilience for urban developments, the Spatial Resilience Toolbox - Flooding (SRTF) can be utilized as a flexible integrated urban design and simulation platform. (Morschek et al. 2019)
The rain runoff simulation is performed by Daniel Piker's interactive physics/constraint solver Kangaroo for Grasshopper. The toolkit can simulate a rainfall event by imbuing particles with a specific mass and gravitational force. The particles are pulled by the external gravitational force during the simulation, resulting in runoff. As a result, the particles seek downward paths similar to rain discharge. They behave like spherules that run off the 3D geometry. (Morschek et al. 2019)

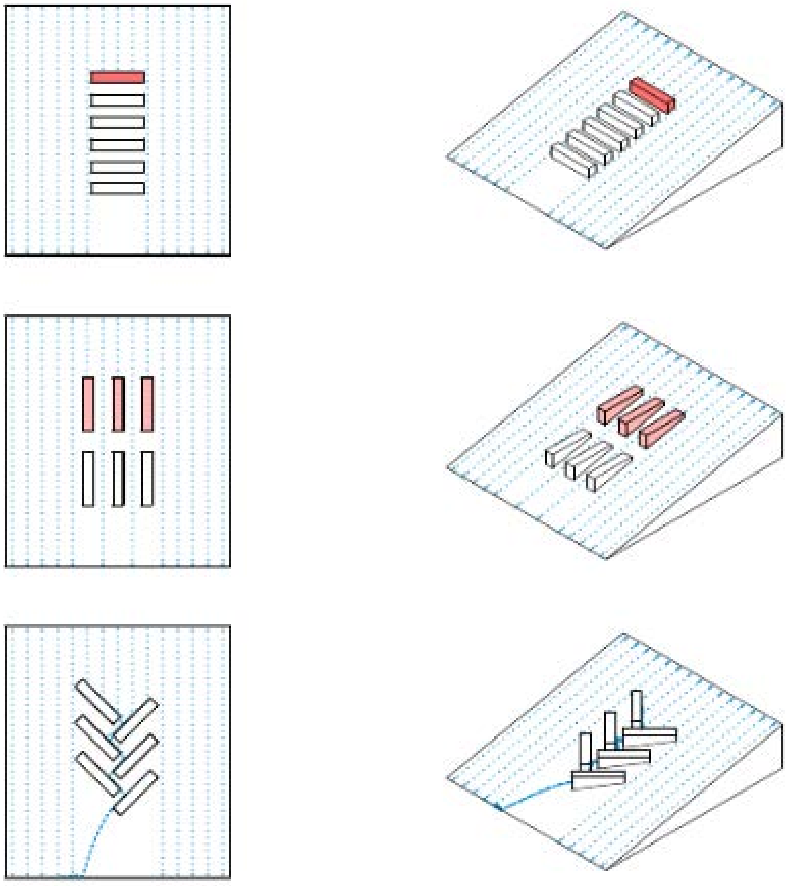


Figure 23. Using the rain-runoff simulation to compare different spatial arrangements based on their behavior during rainfall (Morschek et al. 2019)

Three parameters can be changed to match a variety of rainfall events:

1) the number of particles,
2) particle size, and
3) the number of iterations

The simulation becomes more realistic as the number of particles increases and the size of each particle decreases, but this would take higher computation power and time taken to run each simulation.

A more detailed terrain surface can generate more realistic rainfall runoff results than a less detailed surface. Furthermore, increasing the complexity of the simulations can improve accuracy. Technically, there are no restrictions on the level of detail, such as the number of particles or building shape. However, as complexity increases, so do the processing power and time taken to run each simulation. (Morschek et al. 2019)

Before the simulation can be run, we must first prepare the data and geometries we need to run the simulation.

1) Topography surface mesh
2) 3D Building footprint extrusions
3) Create points, projected onto the topography mesh
4) Join mesh to create the final mesh for the Kangaroo solver to run on.

Step 1 - Creating Topography mesh

The topography Grass is exported as a DXF file from QGIS. It gives Topography curves elevation in the z-axis thus allowing them to be visualised in 3D and be mapped into a mesh.

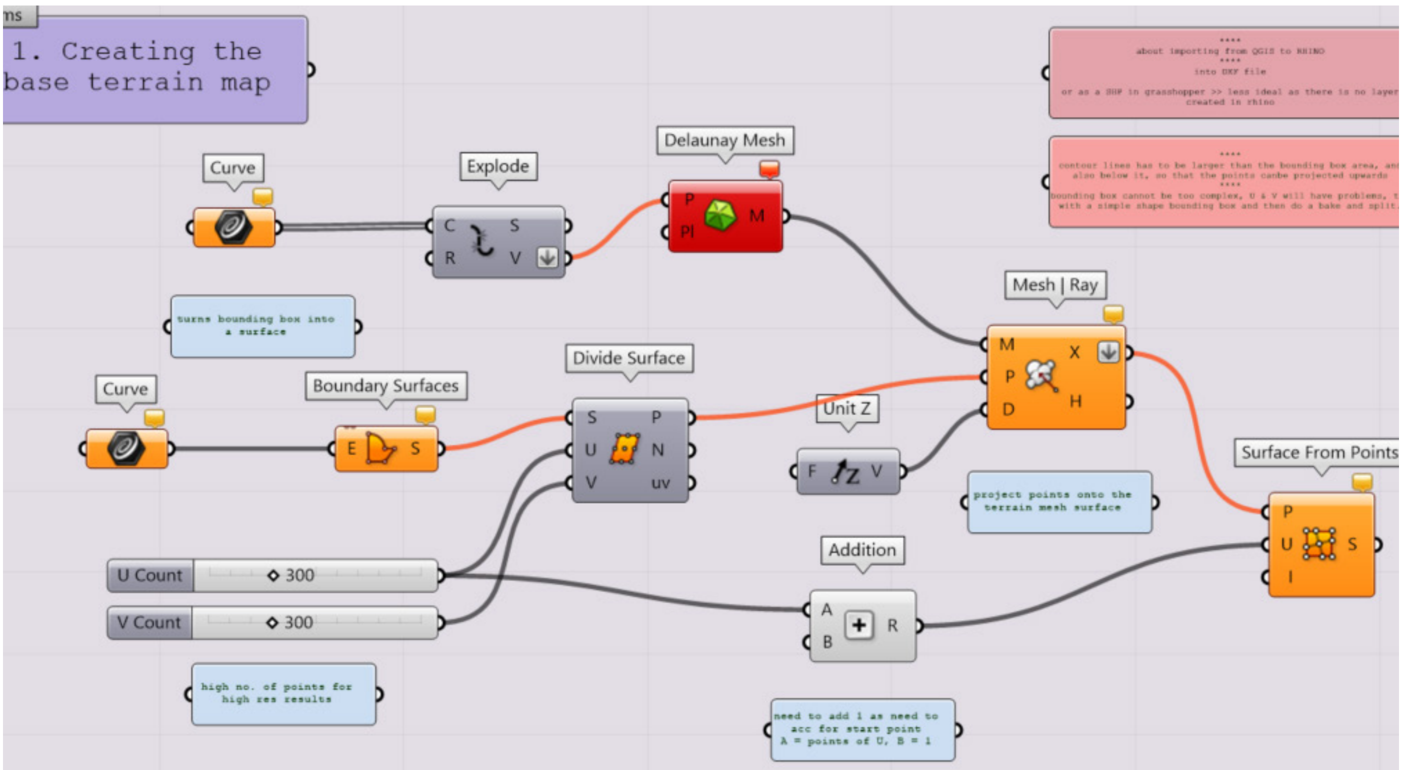


Figure 24. Creating base mesh in grasshopper

Step 2 - Creating 3D Building footprint extrusions

Export Building Footprint information from QGIS, extrude the flat curves in the z-axis. Intersect topography mesh with extrusions to create a cut-out topography mesh

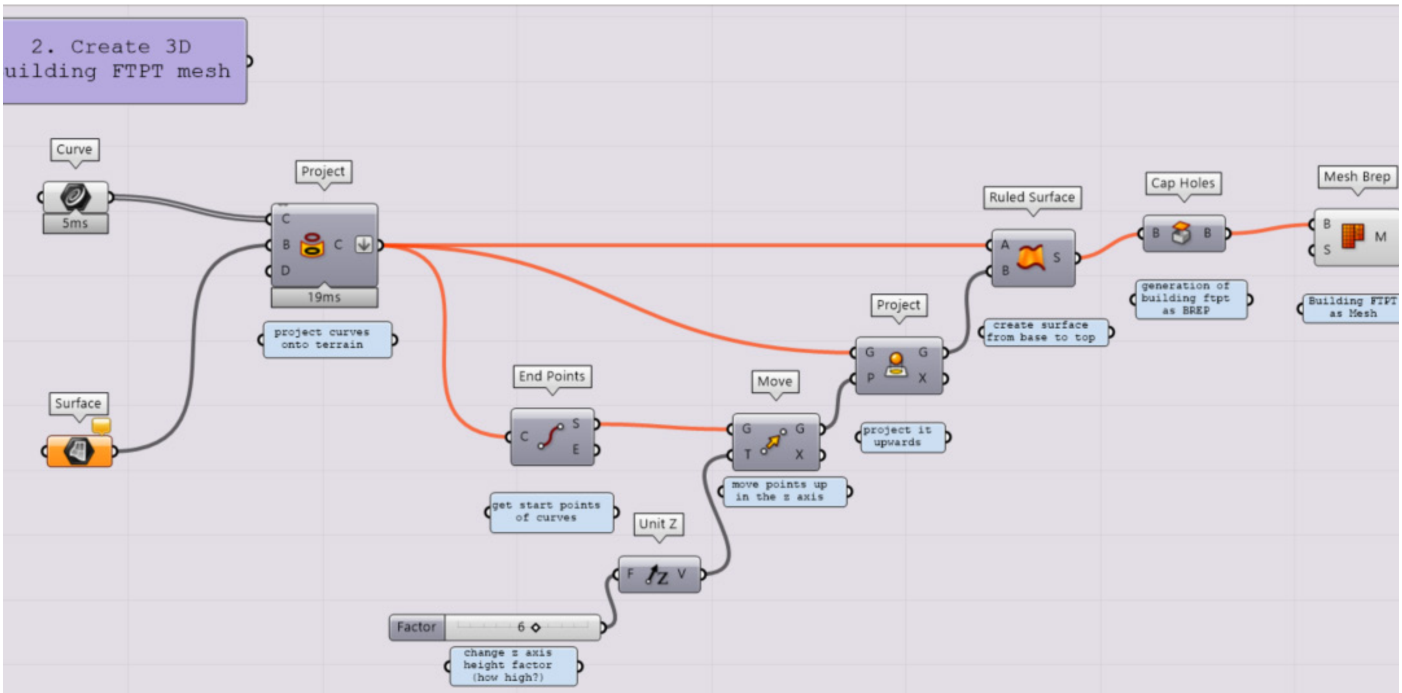


Figure 25. Creating 3D Building footprint extrusions

Step 3 - Create points, projected onto the topography mesh

Divide the surface domain and remap them into centroid points. Project these points that are currently on a flat plane to the curved topography mesh.

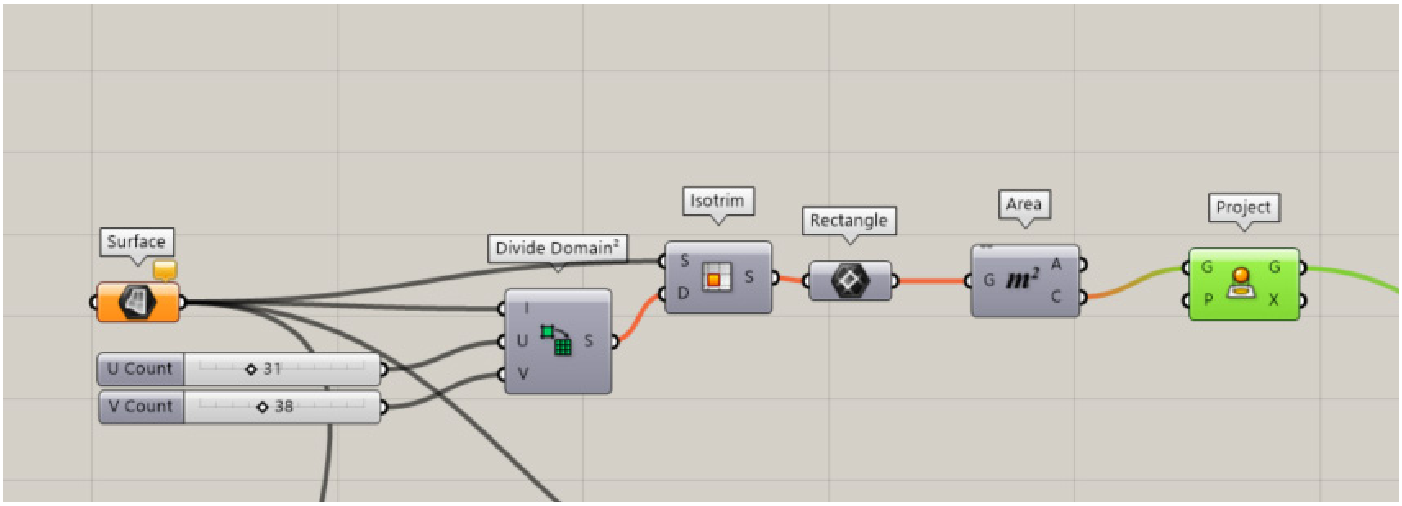


Figure 26. Creating 3D Building footprint extrusions

Step 4 - Join mesh to create the final mesh for the Kangaroo solver to run on.

Join the cut-out topography mesh with the building footprint 3D mesh to create one singular mesh. Project points (raindrops) onto the combined mesh.

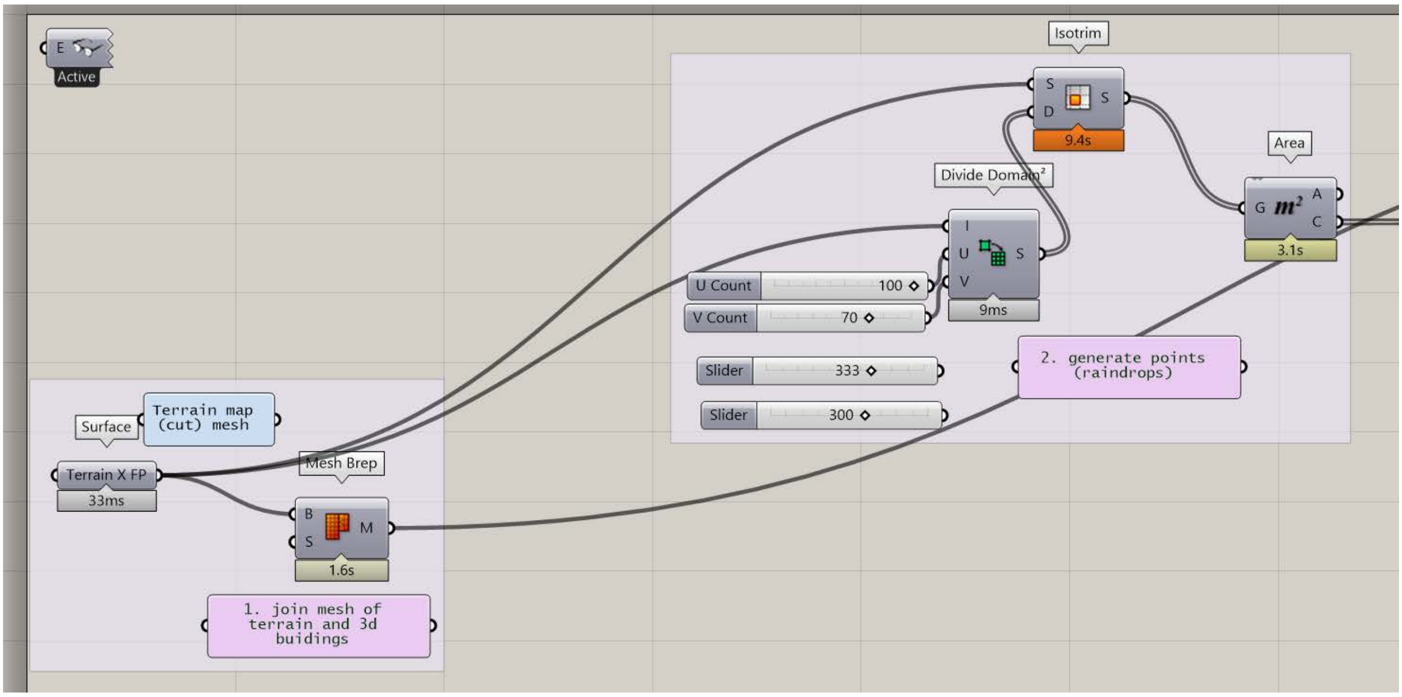


Figure 27. Join mesh to create the final mesh for the Kangaroo solver to run on

The Preparations are complete, and now the Kangaroo Solver can be connected to the script to run the water flow simulation.

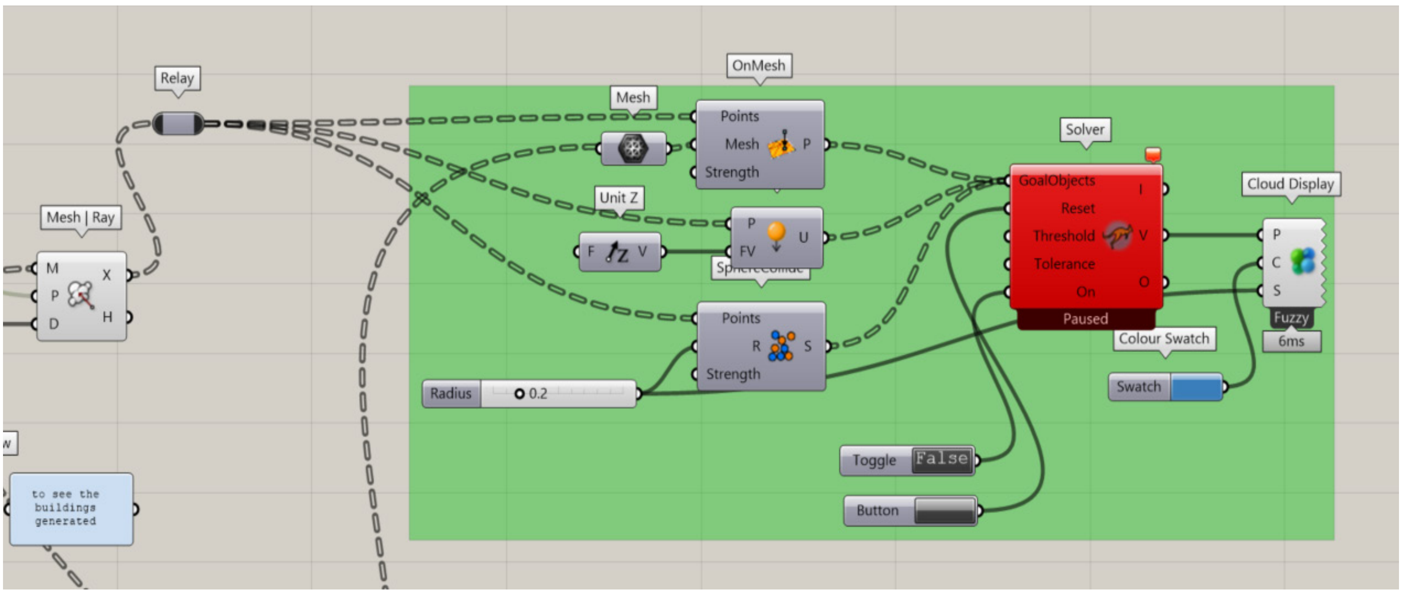


Figure 28. Creating 3D Building footprint extrusions

However, with the regular Kangaroo Solver, only ponding areas can be found. This is because the water flow lines are not tracked and recorded by the Solver. While this result has value in determining where exactly water will run to and which areas would be flooded, the flow lines that could be used to track and manipulate water flow are omitted. Thus, the Kangaroo Step Solver should be used instead.

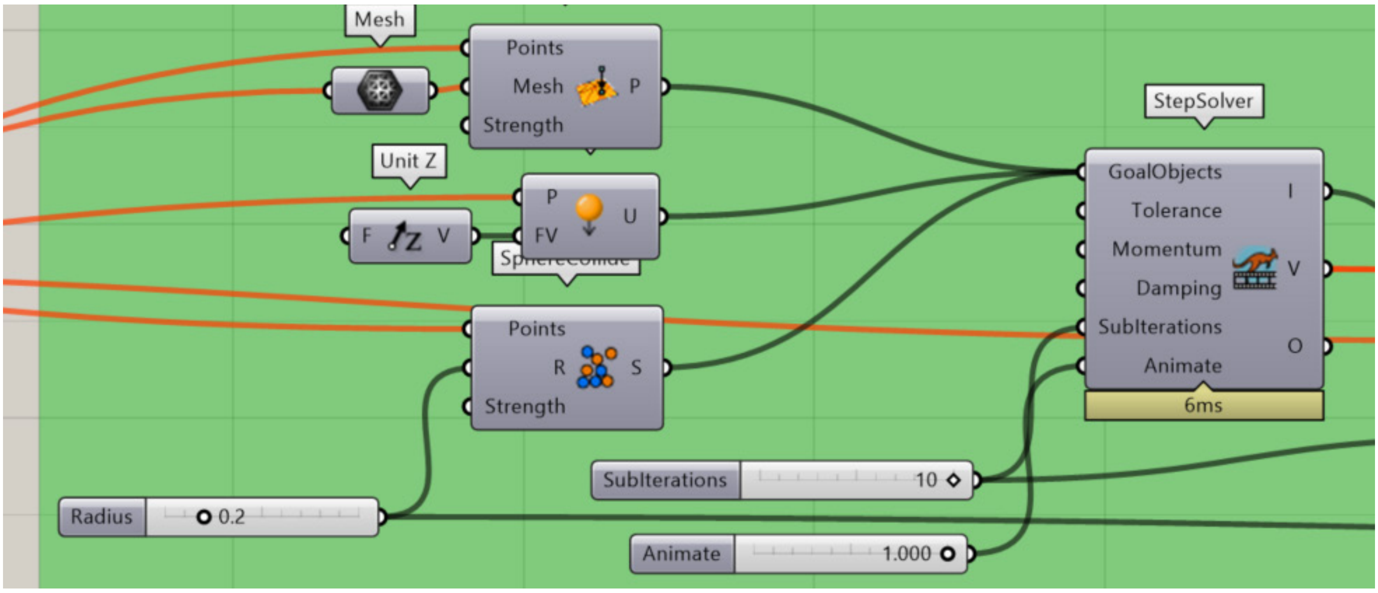


Figure 29. Kangaroo Step Solver

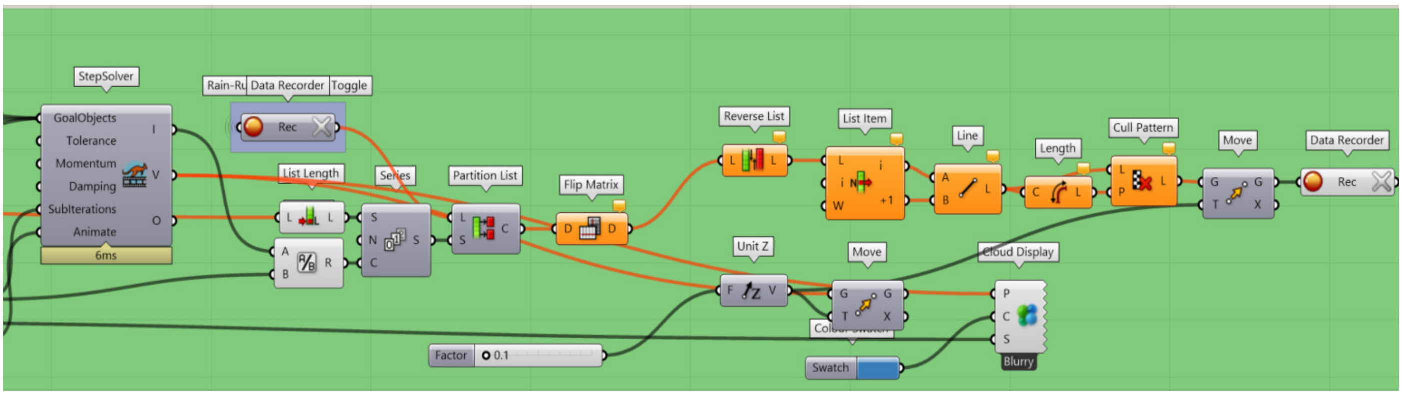


Figure 30. Kangaroo Step Solver - for recording and lines visualisation

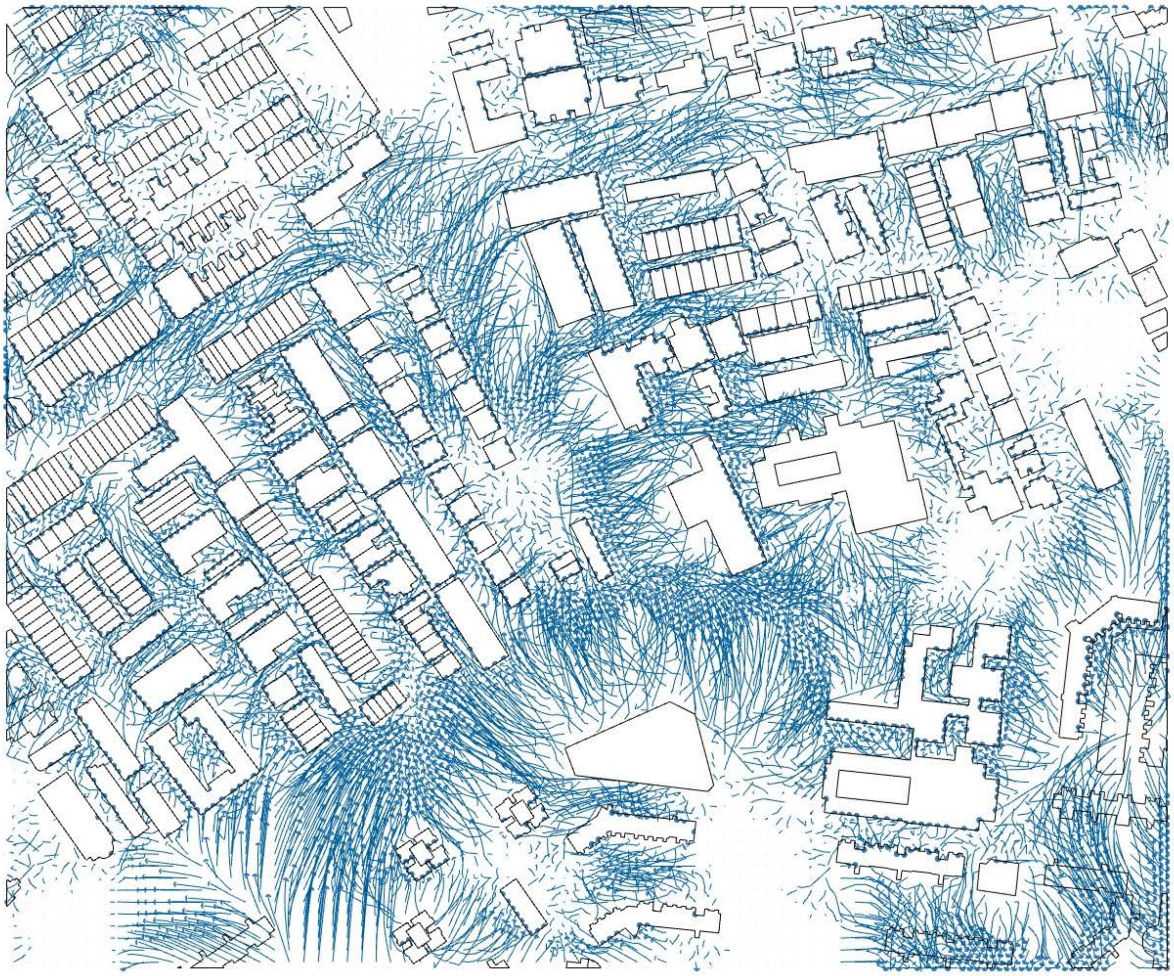


Figure 31. Kangaroo Step Solver results

The animate function in the Kangaroo Step Solver records the flow track of each point and draws a flow line for each water droplet (point). The lines reveal information about intermediate flood channels and major water pathways that many points congregated and took before settling at the final drainage basins, This enables us to better design different strategies to suit different water flow patterns.

4.2. Results

The simulation was first run on the whole site to find potential flood areas and where water could pose a threat to buildings, assuming rainfall happens simultaneously over the whole site at the same precipitation rate.
Even though the building footprint shapes are fairly simple, only the normal Kangaroo Solver can be run on the whole site area due to its large size and the large number of points needed to populate it for an accurate simulation.

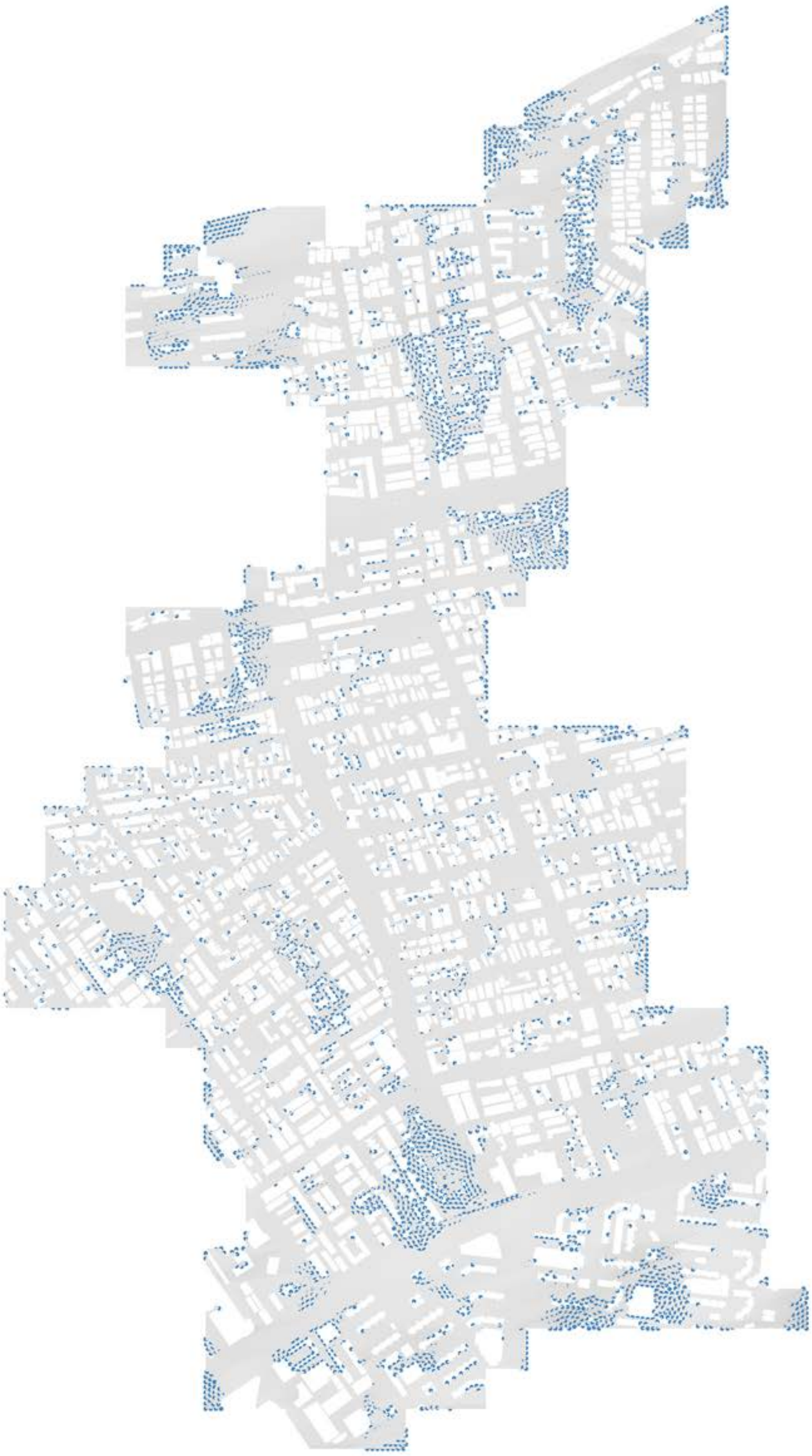


Figure 32. Running the Kangaroo Solver on the whole site

A smaller site near the bottom is then chosen for closer scrutiny and to run the Step Kangaroo solver. This site is chosen due to it having a major flooding area while having a mix of land use and building typologies.

Figure 33.Final selected site for analysis

Other than revealing that water would congregate at low topology areas, the simulation also demonstrates the changes in topology gradients. Areas with zero gradient changes are areas where points remain stagnant. The points in those areas did not move and remained equally spaced. In these areas, the topology is flat and did not have any changes in height, thus water would not flow.

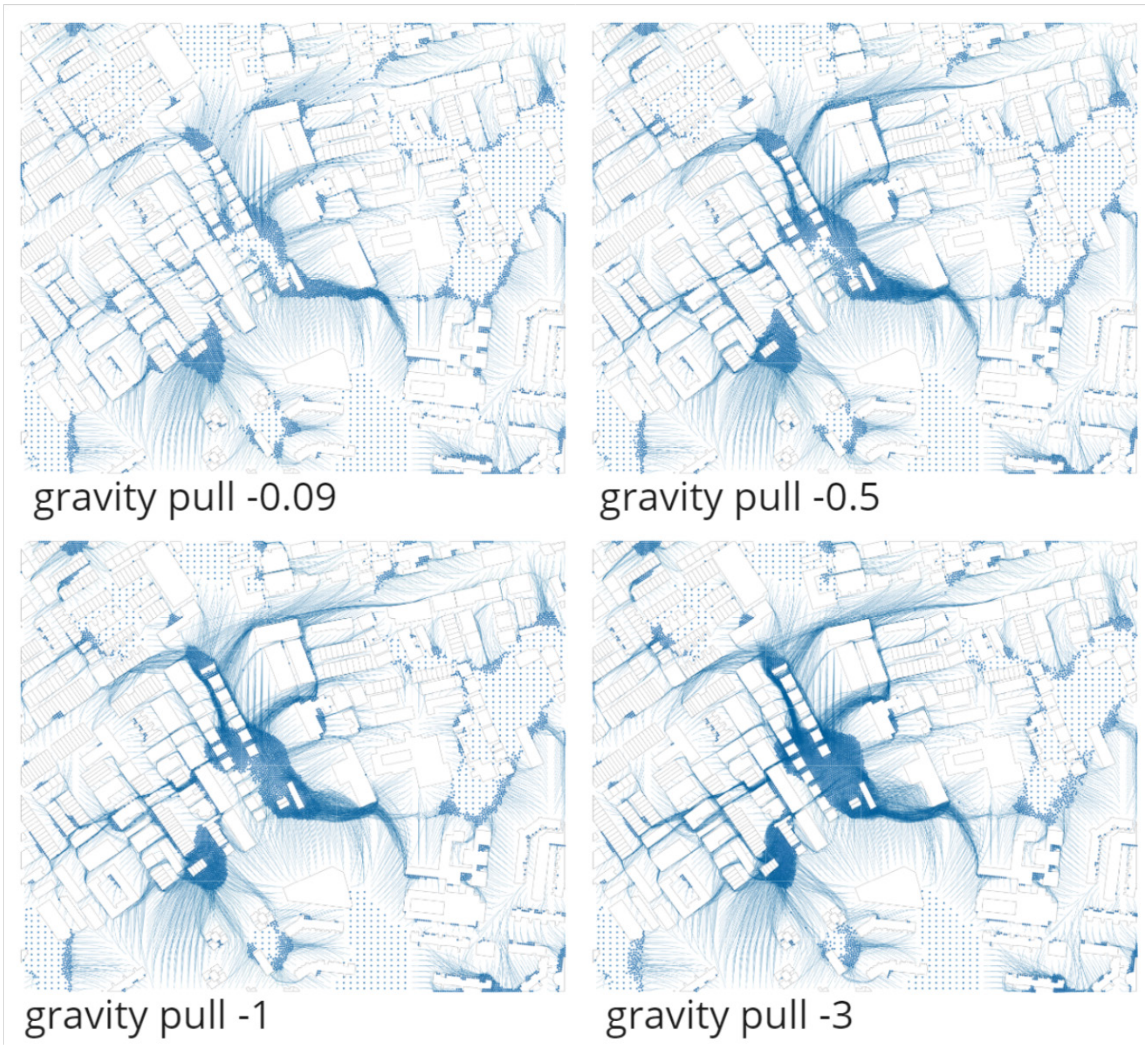


Figure 34. Simulation with different Gravity Factor -
Higher gravity pull allows the simulation to run faster and closer to completion, so GF 3 is selected

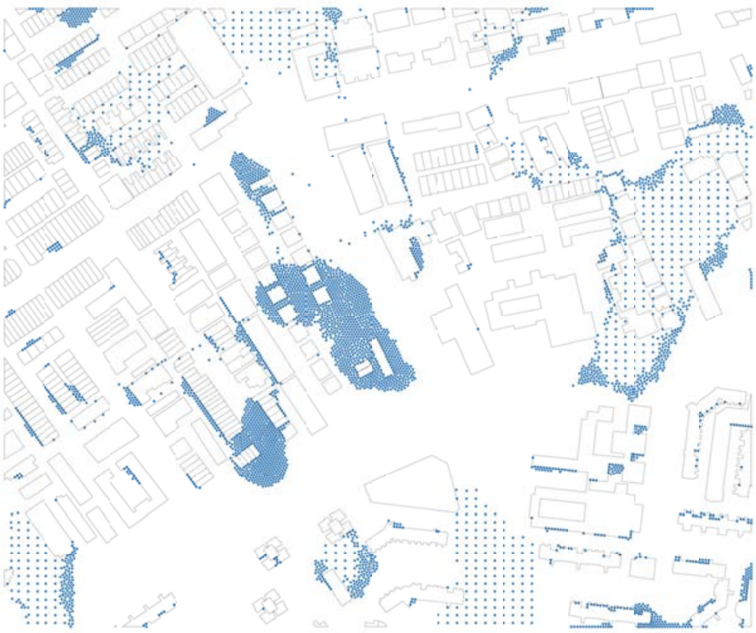


Figure 35. Simulation with just points (flooded areas)

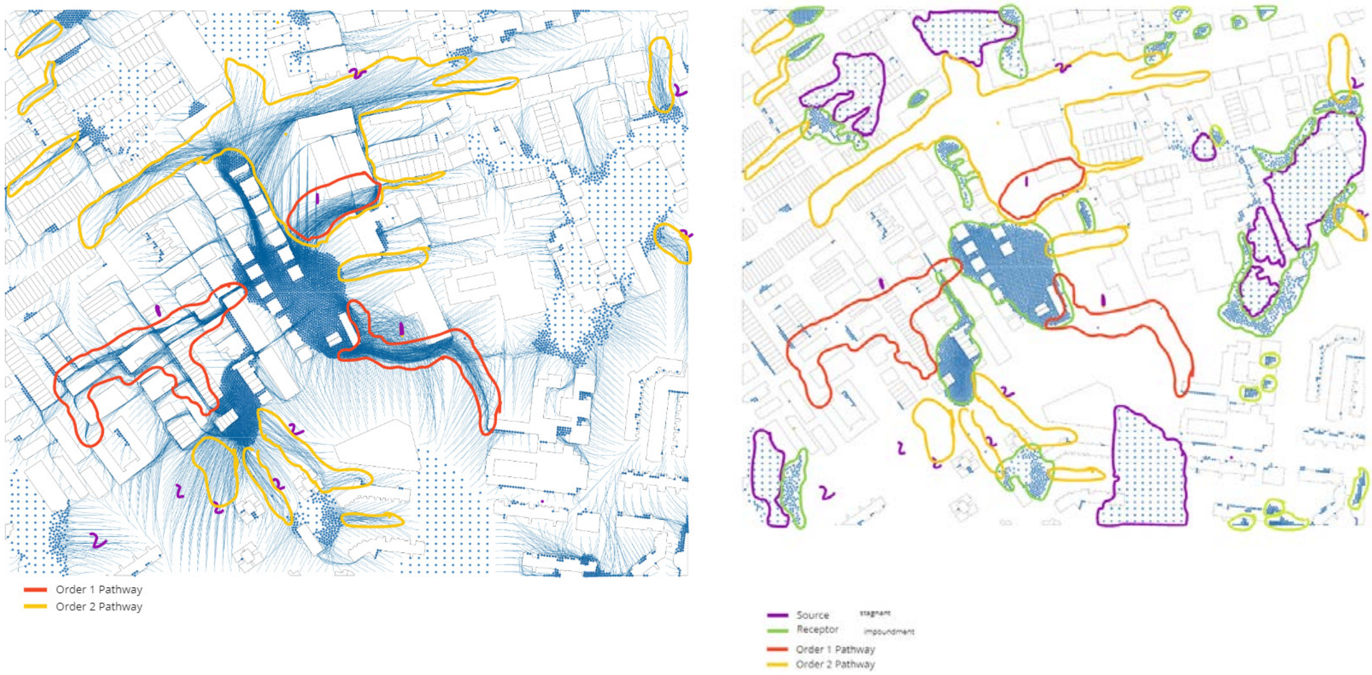


Figure 36. Identification of Stasis areas, Pathways and Impoundments

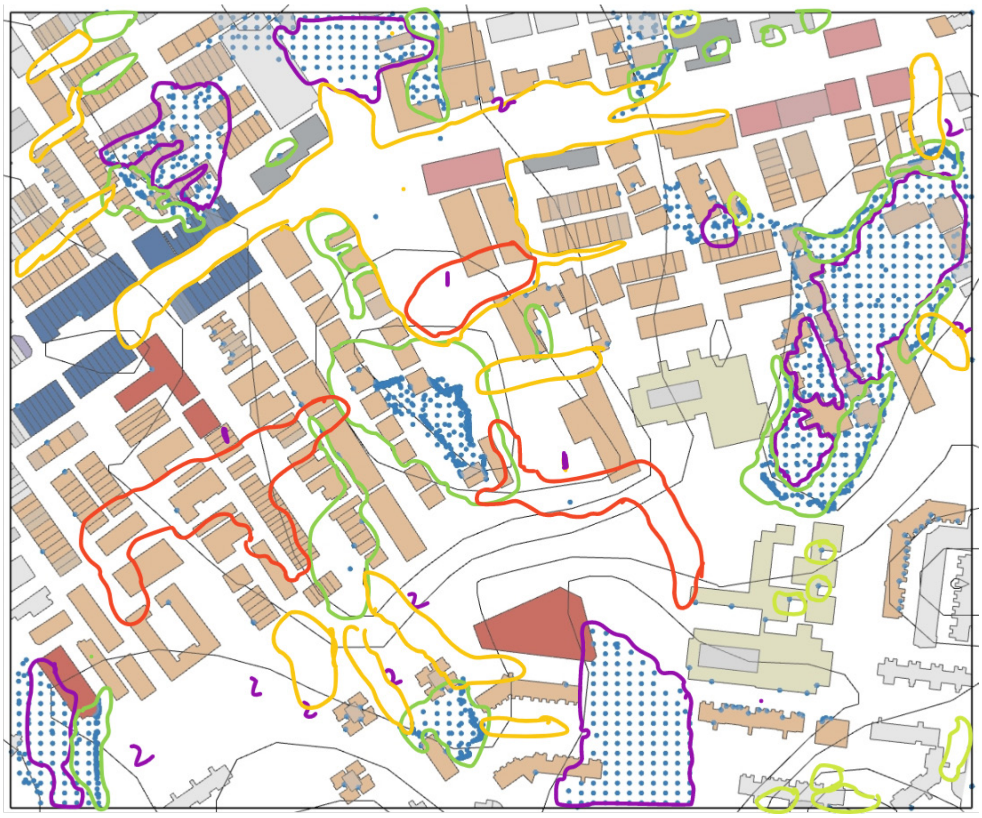


Figure 37. Overlaped with landuse, building footprint, and topological information

The simulation results are then classified into 4 classes:

1) Stasis - water is stagnant, topography does not allow for water flow manipulation, mild ponding

2) Order 1 Pathway - Major water pathways, lots of water come together in these channels before dissipating

3) Order 2 Pathway - less major but still important pathways, water congregate and flow together in these channels before dissipating

4) Impoundment - low lying areas where everything collects, serious flooding.

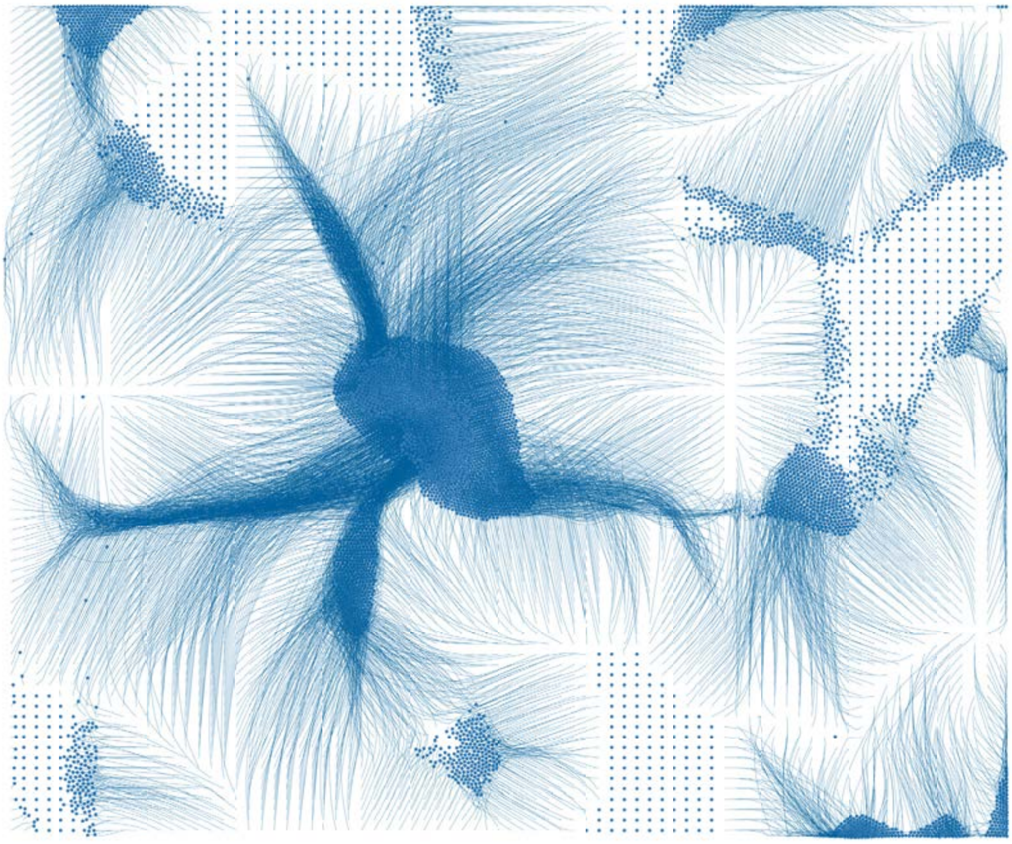


Figure 38. Natural Terrain’s effect on flooding lines

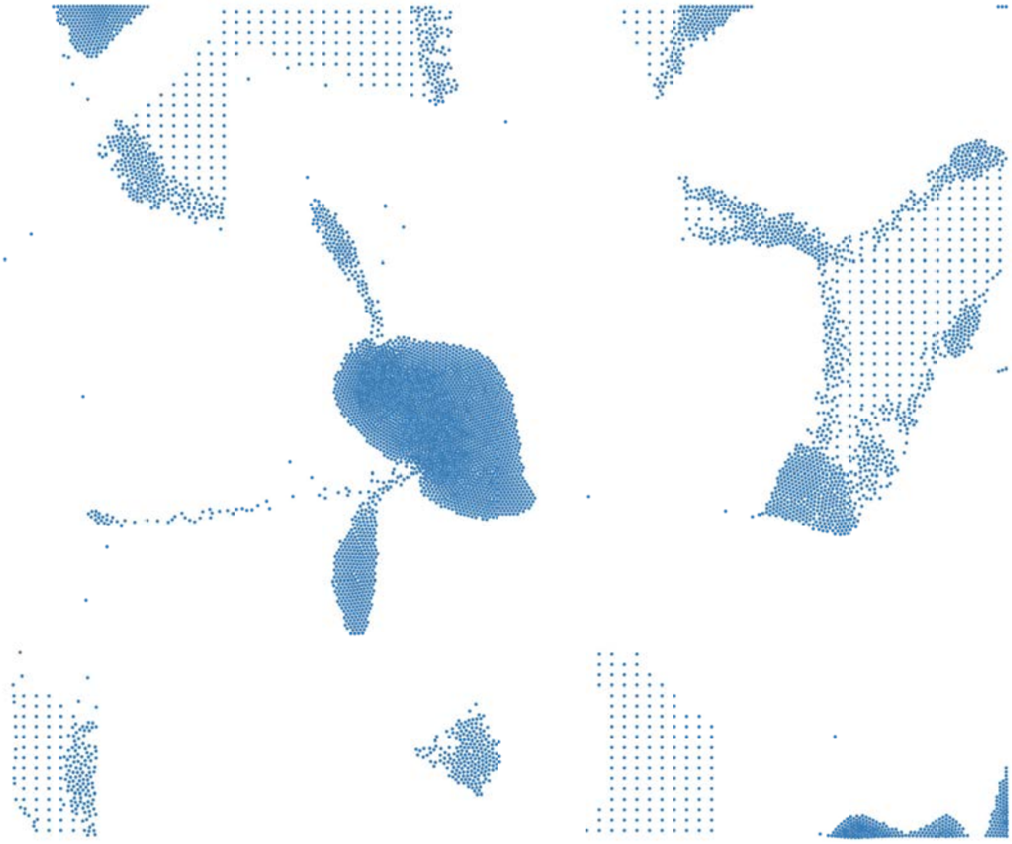
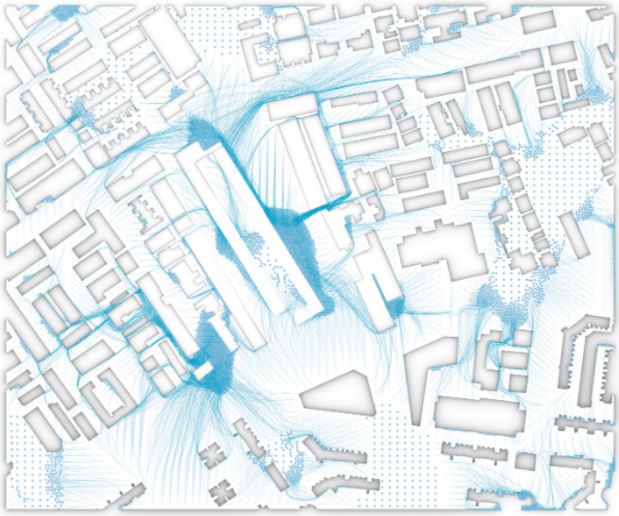
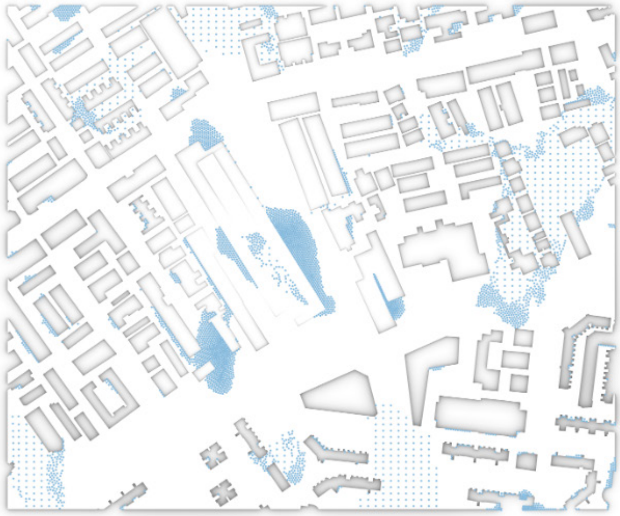


Figure 39. Natural Terrain’s effect on flooding flooded areas

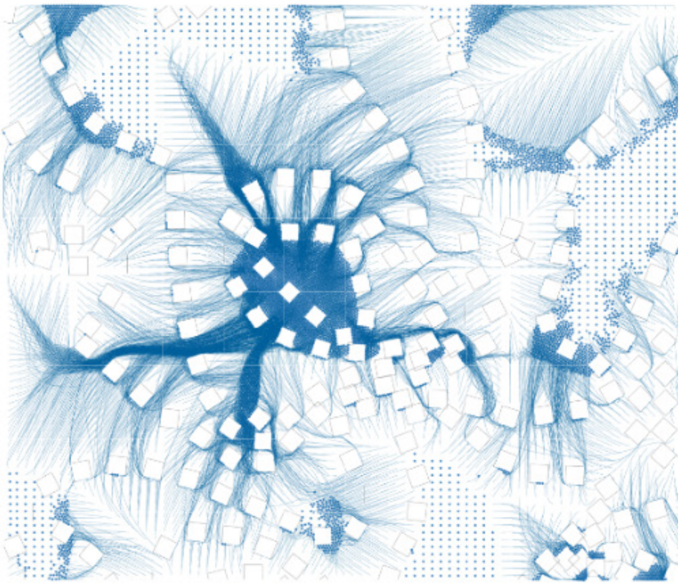
4.4. Discussion

After the hydrological analysis, some alterations can be made to the building footprints and orientations of buildings to attempt to change water flow directions and intensity, in order to reduce the size of flooding areas.





Changing the building footprint of the buildings, either by adding or removing buildings, increasing or decreasing building density has an impact on the water flow and flooding areas. In the above example, the flooding area in the middle has reduced in size. But the floods are now less concentrated and affect other built areas in the district.



Orientating buildings differently can also create an impact on hydrological flow patterns. The above example explores arranging buildings along topo curves, and conforming to a hydrological flow pattern that is closer to the natural water flow created just by the terrain.

From these experiments with the building footprint and running simulations to compare the results generated by each experiment, we can deduce some preliminary findings and strategies that can used in each region.

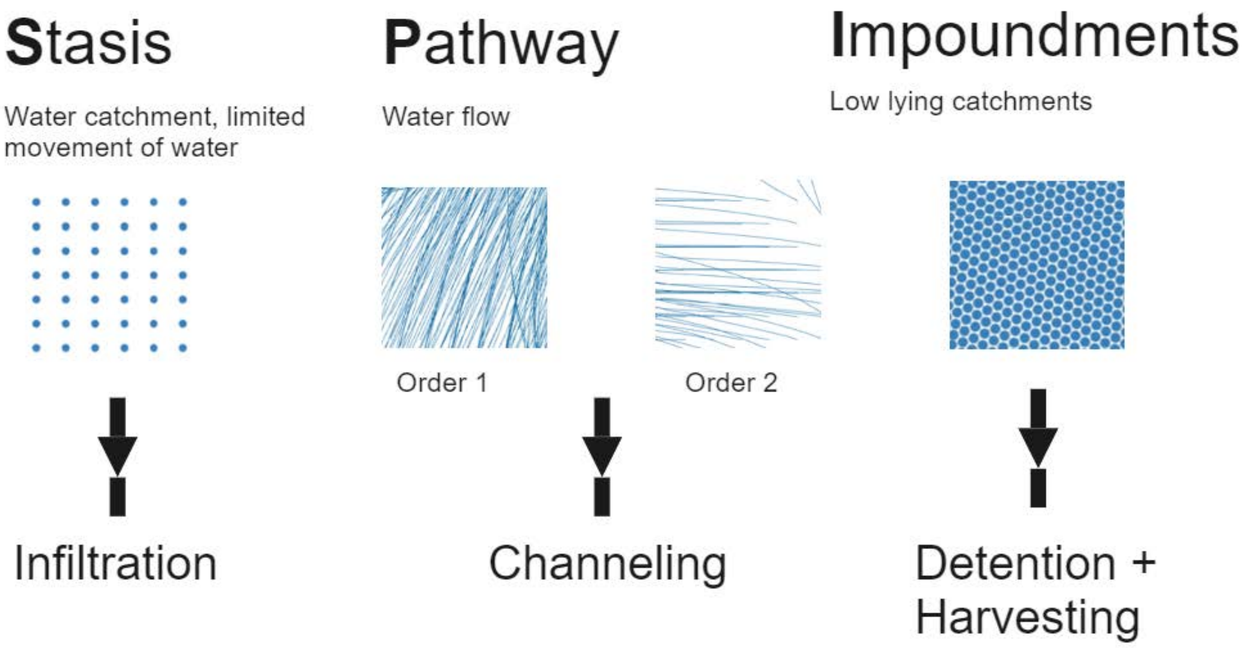


Figure 40. Preliminary general strategies

Overall, the simulations are useful to study water flow patterns and predict which areas might be flooded in the case of heavy rainfall. It was also useful to deduce urban planning strategies that would improve current water flow patterns and to pinpoint exact locations water management interventions should be prioritised.

However, there are some shortcomings to the simulation tool as well. Currently, the simulation tool only takes a few inputs, such as gravity factor, number of raindrops (points), building footprint and land topography. It does not take into account the infiltration factor of each type of surface. Water will infiltrate and seep into the ground much better in green areas compared to impermeable surfaces such as roads, but right now there is no way to differentiate them. Different surfaces should have different flow rates as well, but in the current simulation all surfaces are taken as impermeable and the infiltration rate is at zero.

Current underground drainage systems and canals are also not reflected in the simulations. It is very difficult to find information on the capacity and the locations of the existing drainage system on site. It is also very complex to model, and this level of complexity would further increase the computing power and time needed to run each simulation.

Lastly, building scale strategies and Sustainable Drainage Systems(SuDS) / ABC water design strategies are also not reflected in the simulations. Not only that it is difficult to quantify the effectiveness of these strategies on actual buildings, but they are also difficult to show in simulations that they have been implemented.

Chapter Five: Current Water Management Methods

5.1. Current water mangement methods - an overview

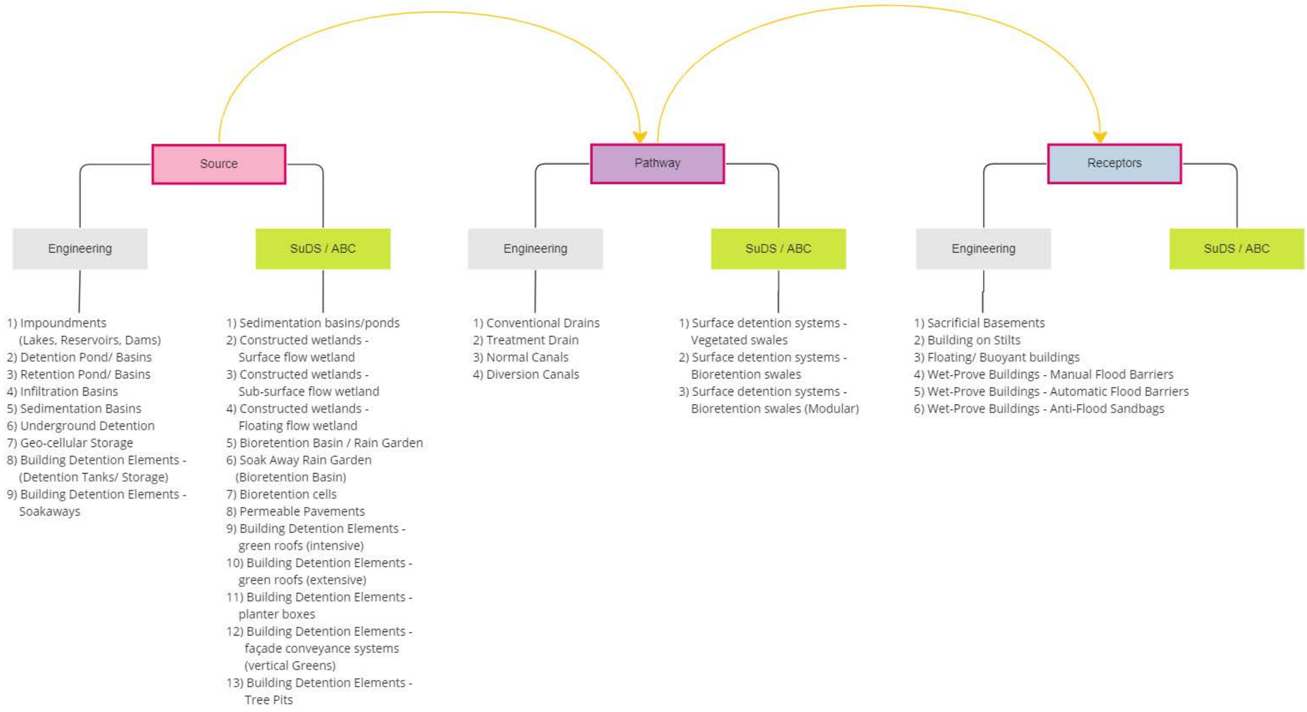


Figure 41. Summary of current water management strategies

Current water management strategies can be grouped into two umbrellas. Sustainable biophilic solutions and Hard engineering solutions. Sustainable biophilic solutions are nature-based stormwater management methods that are gaining traction in recent years. They are touted as a more natural way of stormwater management, with a primary focus on reducing the percentage of impervious cover (%IC) within the watershed, hence increasing infiltration and reducing surface runoff.(Fleischmann 2014)

Sustainable water management strategies go by a variety of names, such as Low Impact Developments (LID) in the US, Sustainable Urban Drainage Systems (SuDs) in the UK and Active, Beautiful, Clean Waters (ABC waters) in Singapore, but they refer to similar nature-based solutions. They have common goals to incorporate natural water bodies (such as wetlands and lakes) and support multi-functional purposes within drainage design (such as improving ecosystem services) while offering extra artificial water bodies and green spaces to increase amenity value.

Hard engineering solutions on the other hand are the typical and more mainstream way of dealing with water problems. These concrete and steel structures deal with water most efficiently, by containing a fixed amount of water or channelling large amounts of water quickly to reservoirs or the sea. Although hard engineering solutions are effective, recently there has been increasing criticism on the over-reliance of engineering solutions.

Firstly, this is due to the inflexibility of the solutions. If a canal is designed to handle the flood amount of a 100-year flood event, it cannot allow for flexibility if the water amount exceeds the maximum that it is designed to handle. Moreover, retrofitting existing hard-engineering drainage infrastructure is expensive and not always possible. The process is also very disruptive. Given the rapidly changing climatic conditions causing 100-yr floods to happen much more frequently, it becomes difficult to speculate an exact number for which these engineering solutions should account. Overcompensation would mean a huge waste of resources, and an underestimate could result in floods that would devastate parts of our city.

Secondly, engineering solutions further disrupt the site's natural hydrologic cycle. As previously stated, flooding is exacerbated by urbanisation and development, where pervious areas have been changed to impermeable surfaces, limiting water infiltration rates. Hard engineering solutions, such as concrete basins and canals, further increase our city's impermeable surfaces, which is counterintuitive and adds to the problem rather than fixing it. Moreover, when poorly planned, hard engineering solutions could create more flooding issues downstream. Especially when several upstream locations experience downpours and concrete channels convey water to downstream areas simultaneously.

Lastly, engineering solutions are solutions that are created to have only one function of water management. It does not contribute to additional ecological, economic or social benefits much like green water management infrastructures would. Furthermore, many consider hard engineering solutions as unsightly and undesirable public spaces.

On the flip side, Sustainable water management strategies has the benefits of:

1) mimicing natural hydrological response to reduce the peak urban runoff and to absorb urban stormwater through soil infiltration, stormwater retention, storage, purification, recharge groundwater and improving the water quality of the runoff. (Chan et al. 2018)

2) integrating natural water bodies (such as wetlands and lakes) and encourage multi-functional objectives within drainage design (such as enhancing ecosystem services and beautifying public spaces) whilst providing additional artificial water bodies and green spaces to provide higher amenity value. (Fleischmann 2014)

Because of these reasons, more and more developed countries like Singapore are integrating Sustainable water management strategies additional to exisitng hard engineering methods.

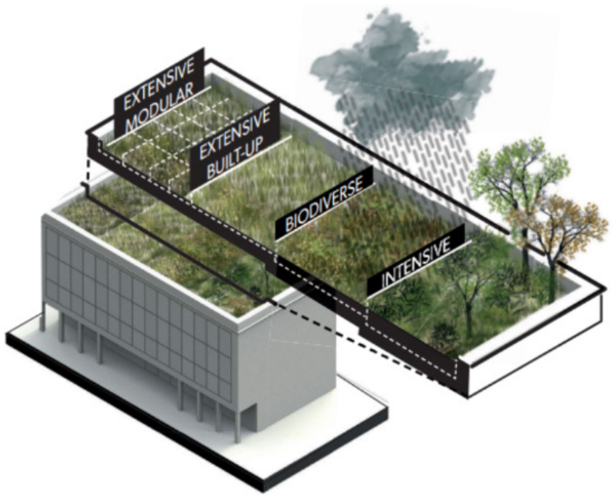
However, it should be noted that Biophilic water management strategies come with its own set of problems. Nature based solutions often require high and regular maintenance. Due to the nature of the solution comprises of living organisms, regular care and resources must be provided to sustain these solutions. It also takes time for the plans to grow and populate the area, before the solution can perform its intended water management functions.

5.2. Source, pathway, receptor

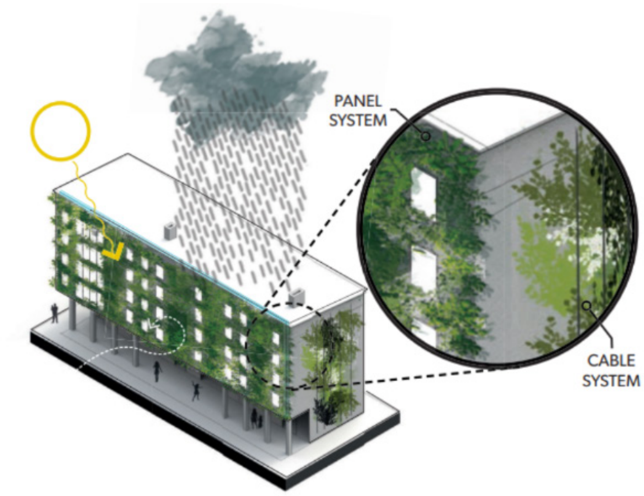
Besides being classified into 2 broad categories of Sustainable biophilic solutions and Hard engineering solutions, solutions can be further organised by where in the water cycle these solutions perform their functions - into Source, pathway, and receptors. Source solutions detain and retain water, attenuate peak runoff, pathway solutions facilitates and slows down water flow, and receptor solutions are building scale strategies that protect buildings from flood water.

Figure 42. The Source-Pathway-Receptor Approach in Singapore's ABC Waters (PUB 2018)

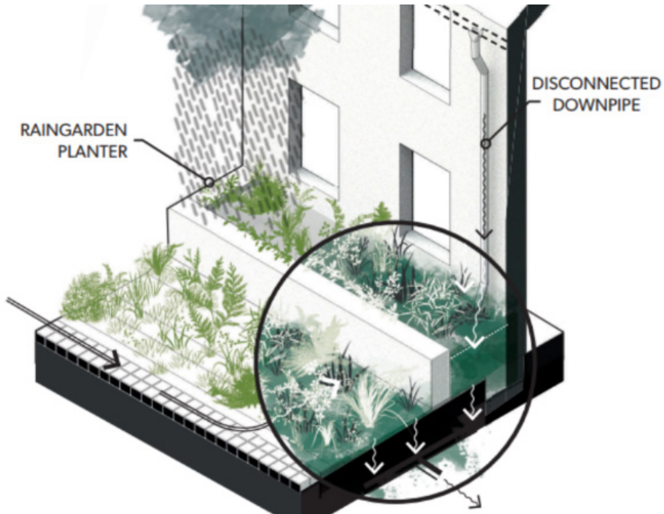
Diagrams showing some of the biophilic water management strategies are illustrated below.



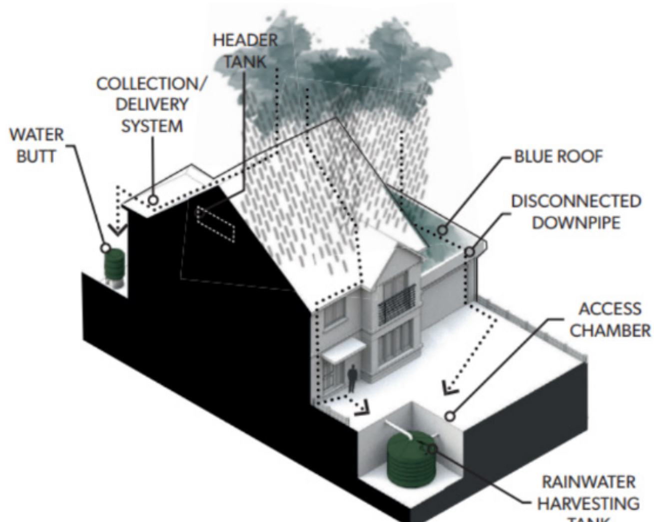
Green Roofs (Barsley 2020)



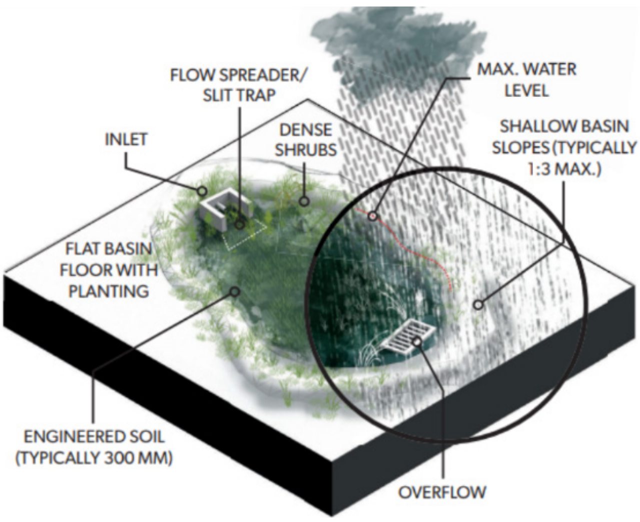
Green walls (Barsley 2020)



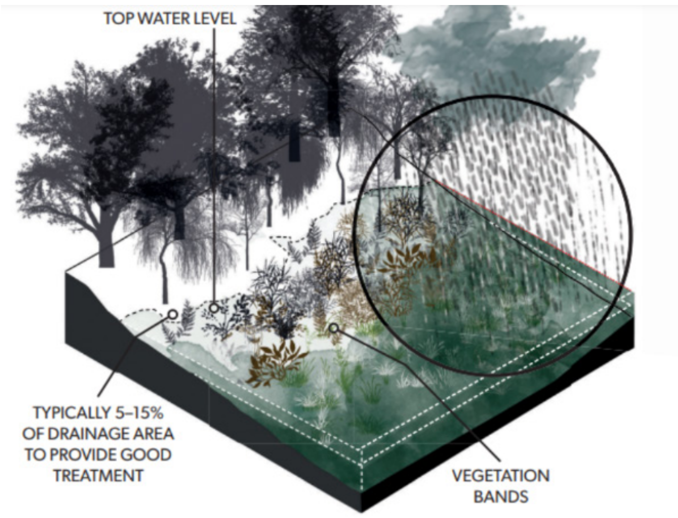
Raingarden (Barsley 2020)



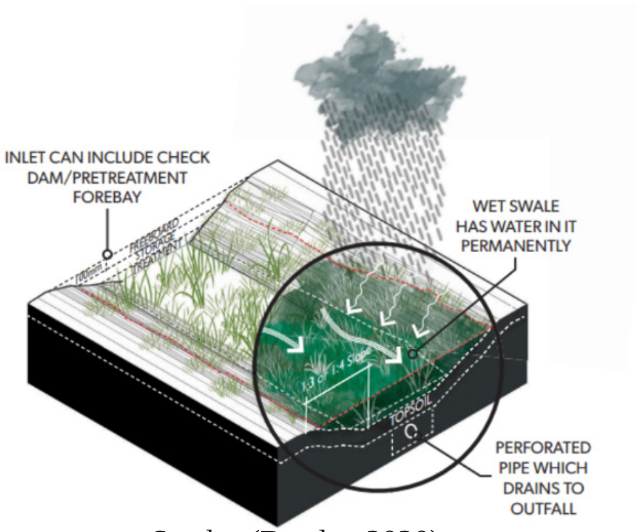
Water butts and water havesting (Barsley 2020)



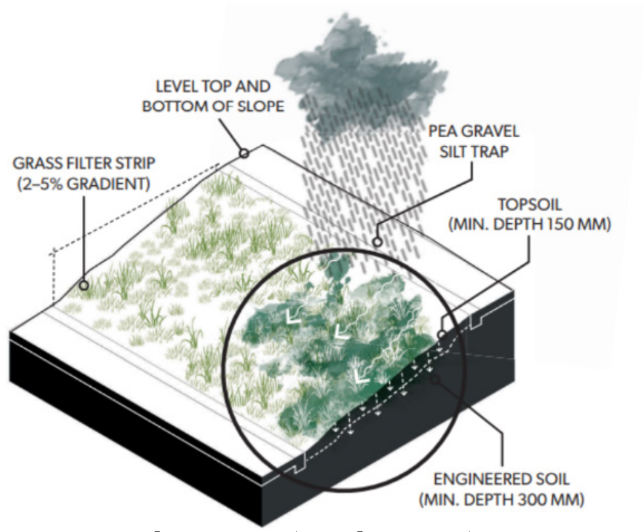
Infiltration Basins/ Structures (Barsley 2020)



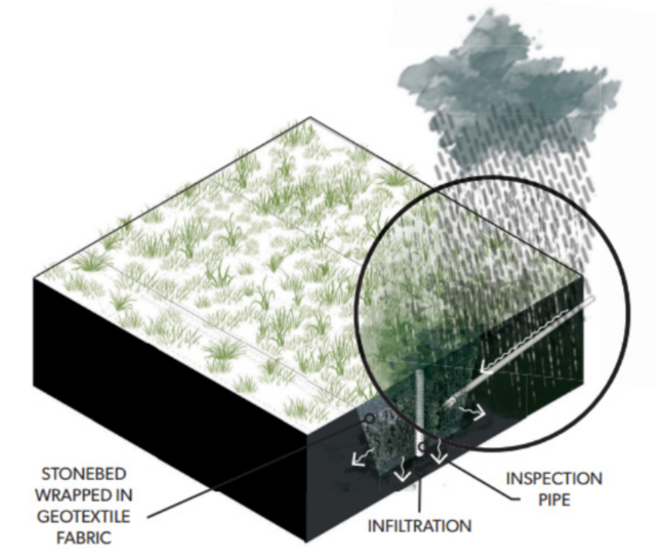
Wetlands (Barsley 2020)



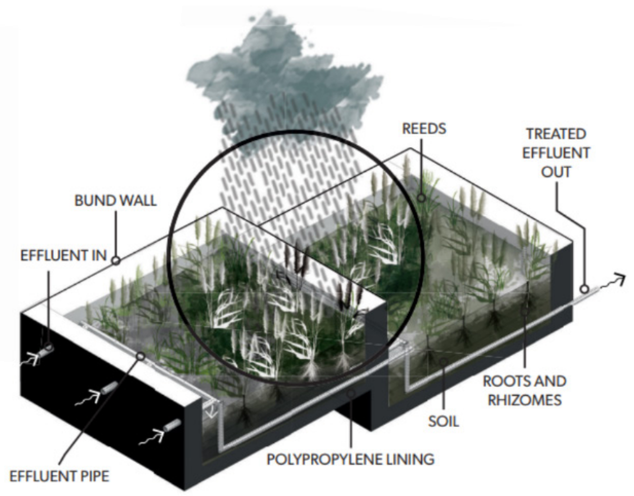
Swales (Barsley 2020)



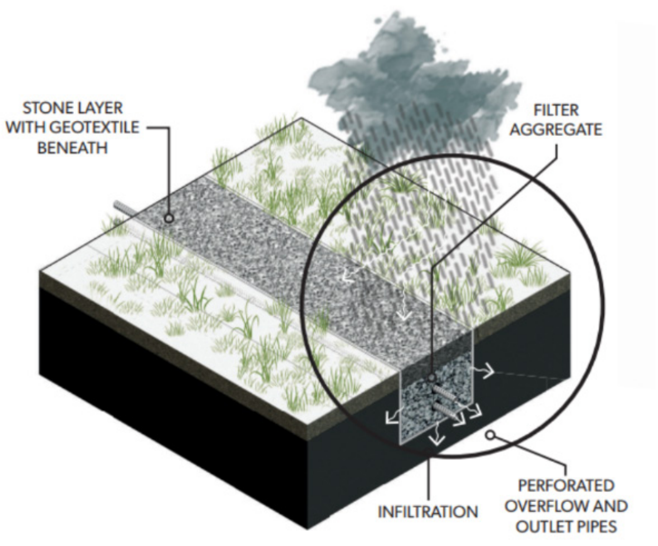
Filter Strips (Barsley 2020)



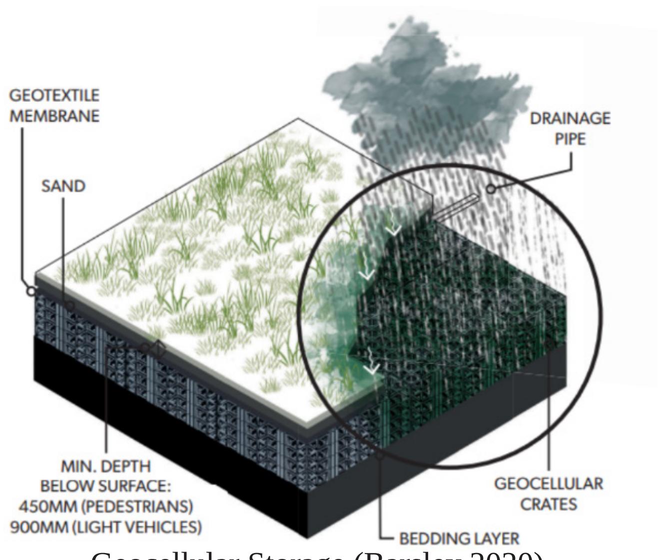
Soakaways/ Infiltration Trenches (Barsley 2020)



Reed beds (Barsley 2020)



Infiltration Drains (Barsley 2020)



Geocellular Storage (Barsley 2020)

Conclusion

In conclusion, the thesis achieved the aims and objectives that it set out to achieve:

Firstly, the development of a new framework to sieve out locations to prioritise for in-land flood prevention - Pluvial Flooding Risk Framework which uses GIS data analysis to identify sites that would pose high risks to human lives and the economy.

Secondly, conduct a detailed hydrological analysis to find out the exact location of the problematic areas within the highest-risk site. The Kangaroo step solver in Grasshopper is used to simulate existing water drainage patterns and to study how building footprint and typography affect the hydrology of the area, some urban strategies with the potential to alleviate flooding are also suggested by evaluating different arrangements of building footprint and orientation against one another quantitatively.

Lastly, this thesis examines some of the currently available drainage infrastructures and suggests some suitable methods that would continue to be relevant in the age of rapid climate change.

This thesis report lays the groundwork for the thesis design project next semester. Knowledge gained from this research would be translated into a design that aims to protect the highest risks areas in Singapore adequately from the impacts of pluvial flooding.

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