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Analysis of urban flooding of core Thimphu Thromde using Storm Water Management Model (SWMM) software and its mitigation measures

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Abstract
Urbanization leads to the transformation of green pastures into impermeable surfaces, resulting in both advantages and challenges. Among the challenges, urban flooding emerges as a significant issue. The rapid urbanization in Thimphu has generated a substantial amount of runoff. Thimphu Thromde encompasses a total area of 26 sq. km, extending from Dechencholing in the north to Babesa in the south. However, this research focuses solely on the core Thromde area, which spans 8.5 sq. km and experiences drainage-related flooding.
This study aims to achieve several primary objectives. Firstly, it seeks to estimate the amount of surface runoff in the core Thimphu Thromde catchment by utilizing historical rainfall data. Secondly, it intends to investigate the relationship between flooding and drainage design elements, such as capacity, alignment, joints, and slope. Thirdly, the study aims to analyze the influence of drain blockage factors on flooding. Lastly, it aims to assess the magnitude of storm drainage flooding, considering both individual factors and combinations of factors, utilizing SWMM software.
A hydrological model was developed using SWMM to analyze the study areas. The study area was divided into 211 urban sub-catchments, and the maximum daily rainfall from each year was employed to assess the existing stormwater drainage flooding. In terms of drainage design factors, the simulation results revealed that alignment and slope were the primary factors influencing drainage flooding, accounting for 72.99% of the occurrences. Regarding joints, out of the total number of junctions experiencing drainage flooding, an average of 7.23% was attributed to capacity, resulting in four flooded junctions per simulation. Upon investigating blockage factors, 10 potential blockage points were identified, with seven out of ten experiencing flooding. The blockage factor contributed to 12.66% of the drainage flooding in the study area.

Keywords: Stormwater drainage, Factors, SWMM model, Urban flooding, Alignment, Slope

Introduction

Urbanization leads to the transformation of vegetated fields into impermeable surfaces, resulting in benefits and challenges. One of the major challenges is the rise of urban flooding. Urban flooding is mainly influenced by urbanization, climate change, and global warming [1]. Furthermore, the Intergovernmental Panel on Climate Change (IPCC) has predicted that global warming will progressively result in more frequent and intense floods and other hydrological extremes [2]. Urban flooding is a major concern worldwide, leading to considerable damage to infrastructure, economic loss, and human displacement. In some of the flooded cities, the water depths were generally in the range of 50-70 cm. The problem is especially severe in Southeast Asia, where the combination of intense precipitation and inadequate drainage systems worsens the situation [3].

The existing stormwater drainage system is inadequate for managing the runoff effects brought on by the shift in land utilization, leading to severe flooding in urban areas during intense storms [4]. Urban development disrupts the natural drainage patterns, displacing the gradual accumulation of rainwater as overland flows toward local streams with impermeable surfaces that channel water through streets [5]. In recent times, the frequency of urban floods has increased due to three key factors: the decreased capacity of drainage systems caused by aging, environmental changes that have altered the hydrological cycle, and reduced watershed permeability due to urban development [6].

Thimphu Thromde spans over an area of 26 sq. km, stretching from Dechencholing in the north to Babesa in the south. However, this study is centered on the main Thromde area, which covers 2.26 sq. km and is prone to drainage-related flooding. The city has grappled with major challenges for an extended period with stormwater drainage, particularly during the monsoon season (Pem. D, 2016; Rai, 2023) [13, 14]. Persistent issues like waterlogged roads, overflowing drains, and flooding after heavy rains have caused major inconveniences for residents and raised concerns for authorities [7]. According to the Stormwater Management Plan for the Thimphu Thromde [8], the poor-quality drains, improper outlet planning, and frequent clogging are primary causes of stormwater flooding. Additionally, some road sections have discontinuous drainage systems, leading to overflows and the deterioration of road conditions. Similarly, [9] also concluded the drainage flooding was attributed to blockages caused by solid waste, insufficient storm drainage capacity, and a poorly designed storm drainage network.

This study aims to identify the primary causes of urban flooding. The amount of surface runoff in the core Thimphu Thromde catchment will be estimated utilizing historical rainfall data. The relationship between flooding and drainage design elements, such as capacity, alignment, joints, and slope will be investigated. Additionally, the study will examine the influence of drain blockage factors on flooding and assess the magnitude of storm drainage flooding, considering both individual factors and combinations of factors, utilizing SWMM software.

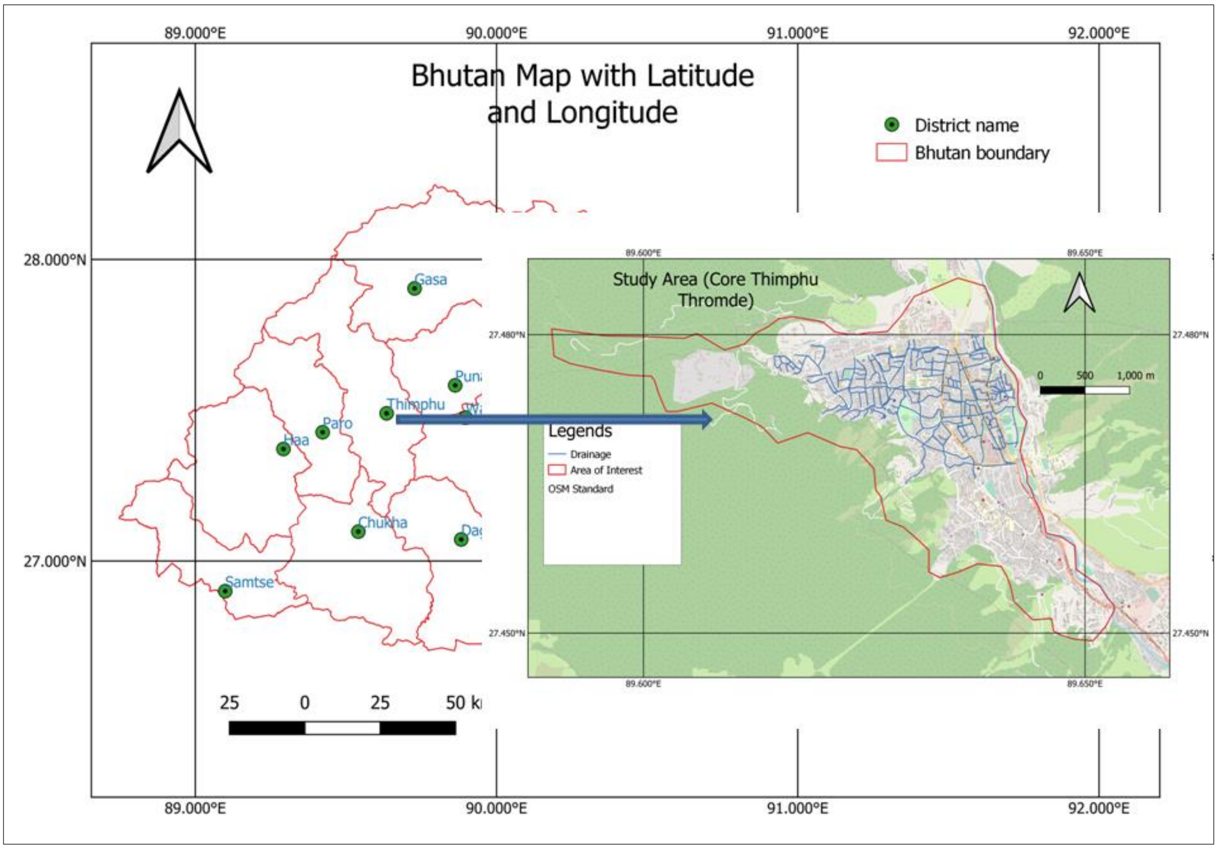

Fig 1: Study Area (Core Thimphu Thromde)

Methods

The objective of the study is achieved by following the methodology outlined in Figure 2.

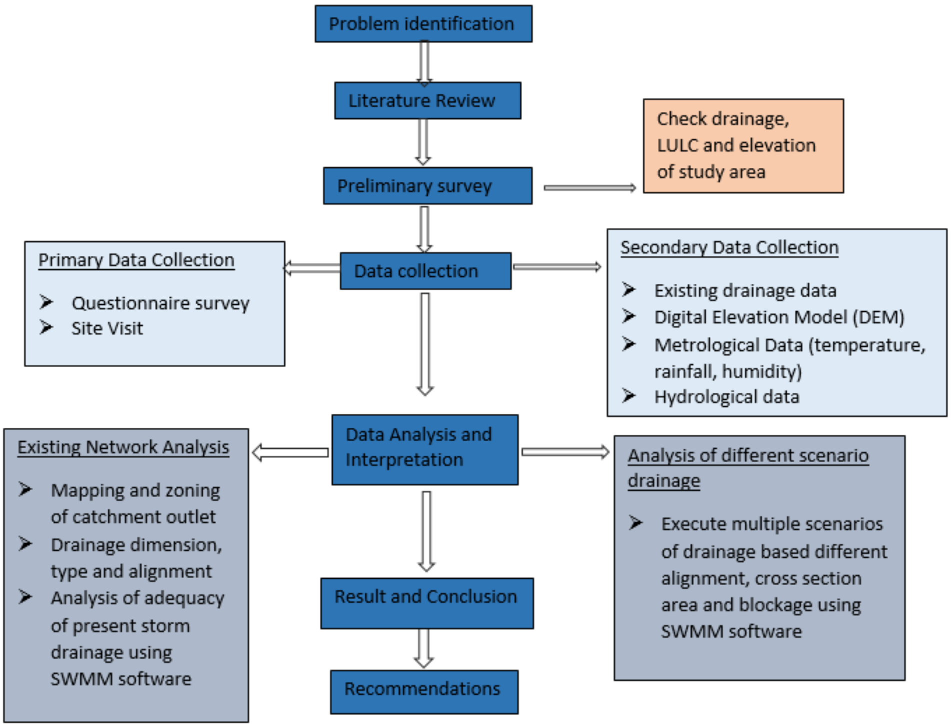

Fig 2: Methodology

Data

The drainage attributes, rainfall data, Digital Elevation Model (DEM), and soil types are essential input parameters in SWMM modelling. Soil type is particularly important for assigning a curve number in the SCS CN method of infiltration. According to a 1997 soil survey by RNR Yusipang, the soil in Thimphu is classified as sandy loam and sandy clay loam. The drainage layout for the entire city was sourced from the National Land Commission Secretariat (NLCS). A high-resolution ALOS DEM (12.5m) was downloaded from ASF Alaska, which is terrain-corrected. Additionally, 15-minute interval rainfall data for 2017, 2018, and 2019 was acquired from the National Centre for Metrology and Hydrology (NCHM).

Parameter Selection

The assessment of any stormwater drainage system should be based on a well-defined set of factors that contribute to urban flooding. These factors must significantly impact the drainage system's performance. This study will focus on the capacity of the storm drainage system and the occurrence of blockages as key factors contributing to urban flooding in the core area of Thimphu Thromde. These factors are influenced by external conditions such as heavy rainfall and urban litter, including trash, debris, and pollutants. Additionally, urban flooding can also result from internal issues like obstructive flow alignment within the storm drainage system, improper slope maintenance along the drainage's length, and structural failures. To address these internal factors, the study will analyze the impact of alignment and slope, considering them as significant contributors to urban flooding.

SWMM Modelling

The urban catchment modelling for the core Thromde area was conducted using the SWMM software, a dynamic simulation model designed to handle both single and long-duration rainfall events, accounting for both runoff quality and quantity [10]. For this study, a single event simulation was employed to identify issues within the storm drainage system. The routing model in SWMM offers three options: steady flow, kinematic wave, and dynamic wave. Since steady and kinematic wave routings are simplified methods that cannot accommodate backwater effects, pressurized flow, flow reversal, or non-dendritic layouts, so the dynamic wave routing was chosen for this project. This approach is capable of addressing all the complexities and phenomena required for accurate modelling.

To model extreme rainfall events, three distinct daily rainfall records were chosen for the core area's hydrological model, with a 15-minute interval between each data point. The selected extreme rainfall events are from the Kuzhugchen station in 2017, 2018, and 2019, and will be used as precipitation inputs for the catchment area.

Sub-catchment Property Modelling

After incorporating precipitation into the project, surface runoff computation relies on the characteristics of the catchment area. The study area was divided into 211 urban sub-catchments based on field data. Each sub-catchment was modelled considering factors such as area, width, terrain slope, percentage of impervious surfaces, Manning's n values for pervious and impervious areas, and infiltration rates.

Initially, the area of each sub-catchment was mapped in SWMM, and the software automatically generated the area values. The characteristics of these areas significantly impact the amount of runoff, as larger areas receive more precipitation, which can contribute to surface runoff. These sub-catchment areas were verified using QGIS after geo-referencing the SWMM base map. In QGIS, the field calculator feature was used to extract the area values. Subsequently, the width of each sub-catchment was calculated using Equation 1, based on the area of each respective sub-catchment.

$$w = \sqrt{A} \quad (1)$$

Where w is the width of sub catchment (m) and A is the area of sub catchment (m^2). The parameter of width governs the concentration time and shape of the hydrograph [11].
The slope of each sub-catchment was calculated using contours derived from the Thimphu Thromde DEM in QGIS. The contours for the study area were generated from the ASF DEM, specifically from the ALOS PALSAR data, which is terrain-corrected. To determine the slope of each catchment, the maximum and minimum elevations within the sub-catchment were identified. The slope was then calculated using the following Equation 2.

$$s = \frac{(El_{max} - El_{min})}{W} \quad (2)$$

Where s is the slope, El_{max} is the maximum elevation of the sub-catchment (m), El_{min} is the minimum elevation of the sub-catchment (m) and W is the width of the sub-catchment (m).
The study area is characterized by heavily paved surfaces, including roofs and highways, which do not allow rainfall to infiltrate, leading to an assumed 100% impervious area. Based on the nature of the pervious and impervious surface areas, each sub-catchment was assigned a Manning's n value appropriate for that area. Manning's roughness coefficients were 0.013 for smooth concrete and 0.15 for short prairie grass. Given the complexity and time-consuming nature of assigning these parameters to each sub-catchment, OSTRICH-SWMM, an open-source tool, was utilized to streamline the calibration process [12].
The infiltration value is determined by the method used and the parameters associated with it. For this study, the SCS Curve Number (CN) method was employed. This method involves parameters such as the curve number, soil group type, saturated conductivity, and drying time. In this context, the soil in Thimphu is classified as loamy sand or sandy loam, which has a moderately low to moderately high runoff potential and a saturated conductivity ranging from 0.06 to 1.42 inches per hour, according to the Hydrology National Engineering Handbook. The drying time, representing the period required for fully saturated soil to dry completely, was set to 7 days for modelling purposes.

Stormwater drainage modelling

Stormwater drainage modelling mainly consists of conduits and junctions to be modelled. Conduits can be modelled in terms of their flow path, cross-sectional area (shape geometry), elevation above the inlet or outlet, length of the conduit, manning's roughness coefficient, and open or closed nature [10]. In SWMM, flow rate is expressed using Manning's equation. For SI units, Equation 3a and Equation 3b are as follows;

$$Q = A \times V \quad (3a)$$

$$Q = \frac{1}{n} A R^{2/3} S^{1/2} \quad (3b)$$

Where Q is the flow rate, A is the cross-sectional area, R is the hydraulics radius, S is the slope and n is the manning's roughness coefficient.
To lay out the flow path of the present stormwater drainage system in the core Thromde area, the plan map of primary and secondary drainage acquired from the NLCS was first overlaid on top of the study area map. Hereafter, to map this stormwater drainage system in SWMM, a map that will be later used in SWMM as a backdrop was created in QGIS along with the world coordinates file. This map is an amalgam of an open street map of the study area and stormwater drainage system. After setting up the backdrop in the SWMM, the conduit mapping phase begins with the introduction of junctions. These junctions serve as endpoints for the conduit sections and represent drainage system nodes, such as manholes in sewer systems or pipe connection fittings. In the core Thromde SWMM model, the junctions are characterized by their invert elevation and height relative to the ground surface. The invert elevation was derived from the terrain-corrected ALOS PALSAR DEM, while the height to the ground surface was determined based on the depth of the conduits connected to the junctions.
Continuing with the conduit mapping, conduits were mapped between junctions using the backdrop created in QGIS. The roughness of the conduit is a critical factor in flow routing, and different Manning's roughness coefficients were assigned based on the construction materials of the conduits. For instance, a roughness coefficient of 0.02 was assigned to concrete conduits. The conduits varied in shape, including trapezoidal, rectangular, and L-shaped designs. The primary drainage system used is trapezoidal conduits, while the secondary drainage employed a rectangular conduit.
After completing the conduit mapping, the study focused on analysing the impact of blockages, which were modelled as weirs. Ten locations within the study area were identified as potential sites for garbage or blockage accumulation. The weirs were modelled as transverse weirs with a vertical opening height of 0.25 meters, representing a 25% blockage in a 1-meter-deep primary drainage. The horizontal length of the weir crest matched the width of the primary drainage, and a discharge coefficient of 1.605 CMS was used. These weirs were then studied to assess their impact on blockages.

Results and Discussion

A total of six simulations were conducted for the project, with three simulations for each of two scenarios. The first scenario was without blockage. In this scenario, simulations were carried out for the years 2017, 2018, and 2019, using high-intensity rainfall data from each year. The results showed that 47 junctions experienced flooding in 2017, 46 in 2018, and 49 in 2019. From these simulations, the frequency of flooding at each junction was calculated. Junctions that flooded in all three simulations were classified as high-risk locations, those that flooded twice were classified as medium-risk, and those that flooded only once were classified as low-risk locations. The flooding junctions were then analyzed to understand the patterns of flooding. Based on these analyses, the junctions were further classified according to the factors that influenced urban flooding events.
The urban flooding classifications were based on factors such as capacity, alignment, slope, and blockage. The slope factor was further subdivided into elevation, ponding, and slope to more precisely represent specific issues encountered in certain drainage sections. The Figure 3 illustrates how the flooding junctions were categorized according to the factors influencing the flooding.

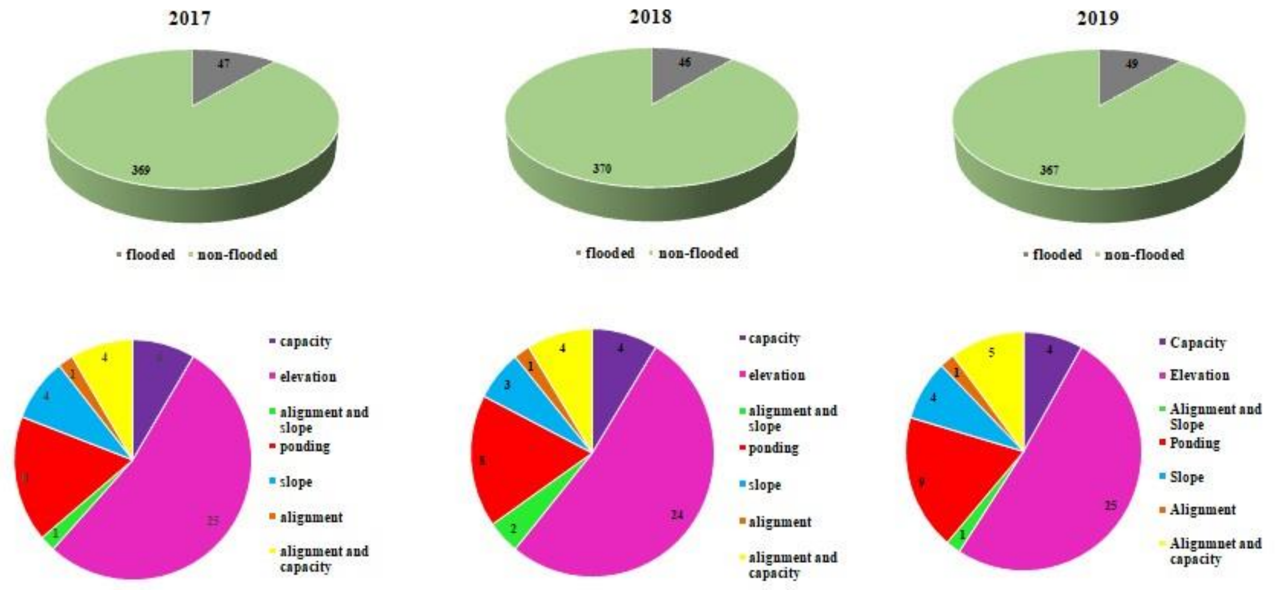

Fig 3: Breakdown of Urban flooding factors

The Table 1 shows how many junctions were influenced due to which factor causing urban flooding in respective years.

Table 1: Frequency table for factors inducing junction flooding: without blockage

Factors	2017	2018	2019
Capacity	4	4	4
Elevation	25	24	25
Alignment/Slo	1	2	1
pe Ponding	8	8	9
Slope	4	3	4
Alignment.	1	1	1
Alignment/Capacity	4	4	5

The second scenario involved simulations where potential blockage points were identified for modelling purposes. In this model, three simulations were conducted using the same rainfall intensity and duration as in the first scenario. In this case, a new factor influencing urban flooding was introduced: blockage. The pie charts below depict the number of flooded junctions for each year, while Table 2 shows the number of junctions affected by each specific factor.

Table 2: Frequency table for factors inducing junction flooding: with blockage

Factors	2017	2018	2019
Capacity	4	4	4
Elevation	26	25	26
Alignment/Slope	1	2	1
Ponding	8	8	9
Slope	4	3	4
Alignment	1	1	1
Alignment/Capacity	4	4	5
Blockage	7	7	7

After analysing the results of all six simulations, alignment and slope emerged as the leading factors causing urban flooding. These factors were subdivided into elevation, ponding, slope, and alignment, and together they accounted for 72.29% of the urban flooding causes. Blockage was the second most significant factor, contributing 12.65%. The percentages of influence for the factors studied are detailed in Table 3.

Table 3: Overall flood contribution %

	Capacity%	Alignment and Slope %	Blockage %	Capacity and Alignment %
2017	7.3	72.7	12.7	7.27
2018	7.4	72.2	12.96	7.41
2019	7.1	71.9	12.28	8.77
Grand %	7.2	72.29	12.65	7.81

Capacity Analysis

The capacity analysis was conducted for two scenarios. First, the results from the simulations without blockage were examined. In this scenario, out of the 416 junctions analysed across the three simulations, a total of 4 junctions failed due to insufficient capacity. The failure occurred right after the storm reached its peak intensity, which was 26 mm/hour in 2017, 39.2 mm/hour in 2018, and 30 mm/hour in 2019. The junctions that experienced flooding were primarily intersection points where multiple drainage systems converged.

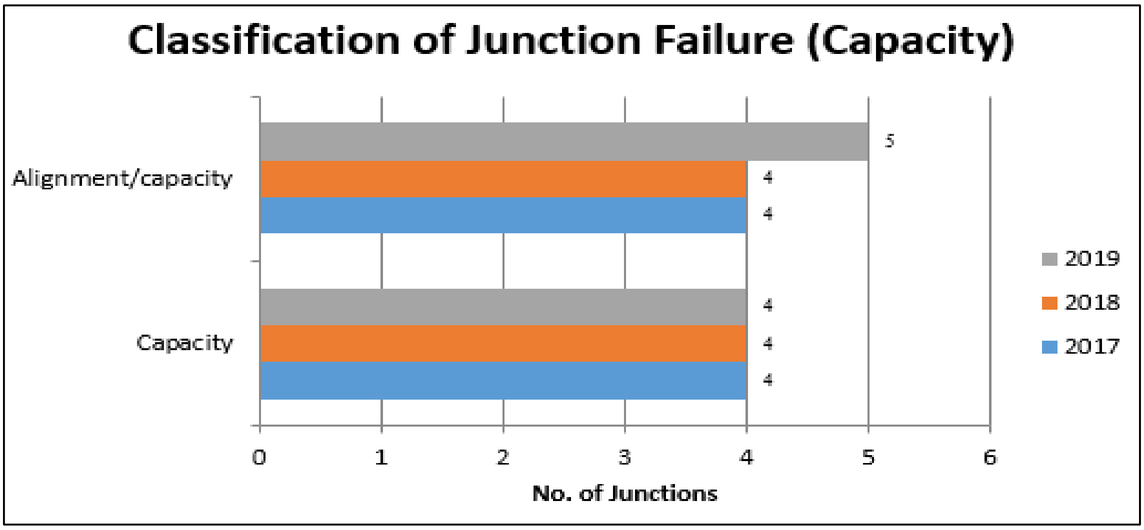

Fig 4: Classification of Junction Failure (Capacity)

In the simulation where weirs were introduced, 4 out of the 420 junctions experienced flooding due to capacity issues during all three rainfall events, as shown in Figure 2. The consistent results between both simulations suggest that the introduction of weirs did not significantly impact overall capacity failures. This indicates that, for the time being, the capacity of the stormwater drainage system is sufficient. However, with ongoing urbanization and climate change, the capacity of the drainage system will likely require reassessment in the future, as noted by Berggren *et al*. When the current stormwater drainage system becomes obsolete and inadequate, expansion and redesign will be necessary, as highlighted by [9].

Alignment and Slope

The causes of urban flooding due to alignment and slope are further sub-divided into: 1. Elevation, 2. Alignment, 3. Ponding, 4. Slope, 5. Combined Alignment and Slope and 6. Combined Alignment and Capacity to better understand the factor in detail.

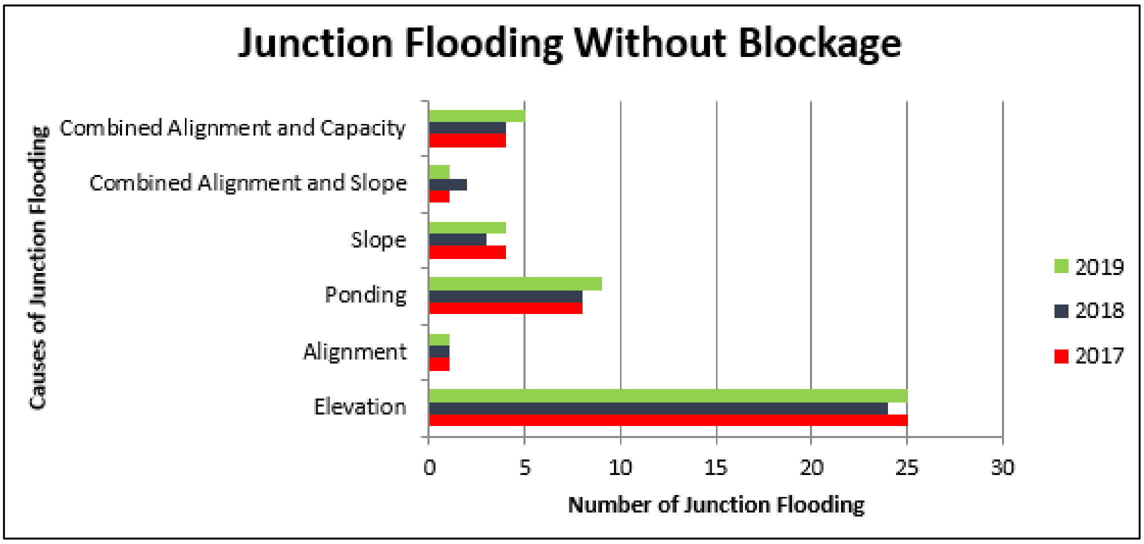

Fig 5: Bar Graph for Junction Flooding Without Blockage

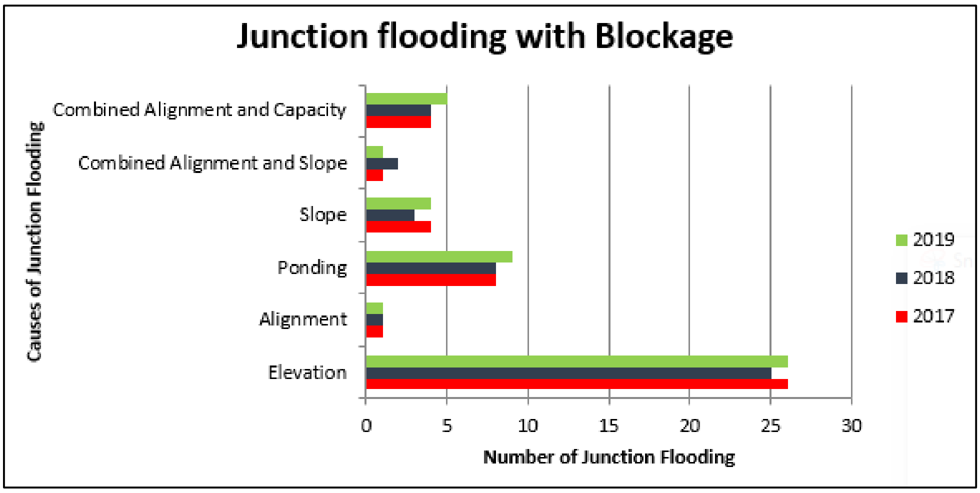

Fig 6: Bar Graph representing Junction Flooding

The bar charts (Figure 5 and Figure 6) visually represent the number of junctions that flooded in 2017, 2018, and 2019, along with the causes of flooding. Among the factors of Alignment and Slope, the sub-factor of elevation was identified as the leading cause of urban flooding, with 25 junctions affected. This was followed by ponding, which caused flooding at 8 junctions.

When blockage was incorporated into the simulation, the parameters of junction flooding remained largely unchanged, except for an increase in junction flooding due to elevation, where the number rose by one. Below are some discussions on the factors related to alignment and slope.

The slope of most storm drains in Thimphu city, which naturally slopes towards the Wangchhu River, generally does not present any issues. The stormwater flows effectively under the influence of gravity. However, in areas where drainage issues due to slope were observed, it was evident that many drains were constructed simply to meet regulations, such as placing a drain near each household or providing an L-shaped drain near roads, without adequately considering the slope and the need for proper water discharge outlets. This issue is reflected in the SWMM simulation results, which correlate with real-life problem areas in Thimphu. These areas often have drains filled with stormwater even during dry periods, highlighting the inadequacy of their design concerning slope.

Some instances of urban flooding were also caused when stormwater flowed from steep slopes and then transitioned into gentler slopes. This transition, represented in the bar graph by the combined factor of alignment and slope, led to spillage. The flooding occurred due to the supercritical flow condition of the stormwater as it moved from the steep slope to the gentler slope, causing overflow at the transition point.

The layout of Thimphu's stormwater drainage system clearly highlights alignment issues, reflecting the early stages of urbanization in the city. The drainage system was constructed haphazardly, with little consideration for proper alignment. In many areas where stormwater from different regions converges, the drains were connected at a 90-degree angle. This poor alignment caused stormwater to spill over the drains, leading to flooding and inefficiencies in the drainage system.

Urban flooding caused by ponding in Thimphu city primarily occurred when stormwater was unable to flow through adjacent conduits because the water needed to move upward. This resulted in stormwater stagnating at specific locations, leading to overflow along the sides of the drains. In some cases, ponding also happened when water from impervious surfaces, such as roads and footpaths, could not properly drain into the storm drains.

Urban flooding due to elevation issues is somewhat similar to ponding but with a key difference. Instead of water remaining stagnant, the stormwater is forced to backflow when it encounters higher elevations in adjacent conduits. This backflow also contributes to urban flooding, as the stormwater cannot continue its intended path and spills over into surrounding areas.

Blockage analysis

Blockage failure occurs when garbage or litter obstructs the flow path in a stormwater drainage system, leading to reduced discharge and an increased water level upstream. This situation is particularly problematic because significant blockages can result in the complete obstruction of the flow path, causing flooding in the upstream sections of the drainage system. When a drain is blocked, water tends to stagnate in lower elevation areas of the drainage system. During high-intensity rainfall, this blockage obstructs the flow, leading to overflow throughout the drainage system.

Analysis from three rainfall events showed that at locations where weirs were introduced, the flow rate decreased from an average of 0.702 CMS to 0.425 CMS. This reduction in flow rate led to an increase in the depth of flow upstream, raising the likelihood of flooding. For this study, 10 locations within the stormwater drainage system were identified as potential points for garbage accumulation, which could lead to blockage and subsequent flooding.

According to a news article, Thimphu often experiences clogged drains and flooded roads during monsoon rains. The results from three simulations indicate that blockage contributed approximately 12.66% to the overall flooding scenario. If more potential blockage points are identified, the projected impact of blockage could be even higher.

Among the 10 potential blockage points examined, 7 experienced flooding due to blockage in each simulation, representing 70% of the total points. This suggests a 70% probability of flooding at a potential blockage point. Blockage can also be attributed to irresponsible waste disposal by residents. To address this issue, implementing covered drainage systems and establishing a routine for daily cleaning of stormwater drains could help reduce blockage and urban flooding.

Additionally, a probabilistic approach, such as Monte Carlo simulation, has been shown to be more efficient and cost-effective than traditional hydraulic methods, as noted by Yazdi. Adopting this probabilistic approach could be a valuable next step in addressing the blockage problem.

Table 4: Percentage of potential junction flooding due to blockage

Year	Potential Blockage Points	Potential Actual Blockage Points	Probability of Flooding (%)
2017	10	7	70
2018	10	7	70
2019	10	7	70

Conclusions

The comprehensive study on urban flooding in Thimphu Thromde exposes several factors causing urban flooding. The current drainage system fails in alignment and capacity to discharge high-intensity rainfall and impervious pavement surface runoff. The unplanned construction of drains for future anticipation, often connected at 90-degree angles, leads to inefficiencies and overflow. Similarly, the simulation reveals drains were constructed without adequate consideration of slope. It was found that the cause of flooding at 25 junctions was mainly due to slope issues. The simulation results reveal the alignment and slope were the major factors influencing the urban flooding in Thimphu city accounting for 72.29 %. Another factor implicating flooding is blockage caused by garbage accumulation in stormwater drains. This accounts for approximately 12.66 % of the overall flooding scenario. The comprehensive approach includes infrastructure improvement, community engagement in waste management and urban landscaping measures could enhance the resilience of the drainage system against urban flooding.

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