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Assessing Flood Risk in Thimphu: Analyzing Contributing Factors through Urban Flood Modeling

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Abstract - Thimphu City is grappling with a growing problem of urban flooding due to rapid development. The increase in impervious surfaces and resulting runoff has led to overflowing storm drainage systems that have been in place for the past two decades. The objective of this study is to determine the factors that contribute to urban flooding in Thimphu City and identify the specific sites that are most affected. To accomplish this, a hydrological model of the study area was created using SWMM software. The study area was divided into 211 urban sub-catchments and the daily maximum rainfall from each year was used to assess the current state of the stormwater drainage system. The study focused on locations that had previously experienced urban flooding and were chosen as major sites for investigation.

The factors contributing to urban flooding were analyzed, with a focus on the drainage capacity, alignment or slope of the drainage, and blockages in the system. It was determined that the alignment and slope of the drainage system were the primary factors contributing to urban flooding, accounting for 72.29% of incidents. Blockages in the drainage system were found to be a factor in 12.66% of cases.

This study highlights the importance of considering the alignment and slope of storm drainage systems in urban planning to mitigate the risk of urban flooding. It is recommended that drainage systems be designed with a slope that facilitates water flow and that regular maintenance is performed to prevent blockages. These measures will go a long way in reducing the impact of urban flooding in Thimphu City.

Key words: Stormwater drainage, Factors, SWMM model, Urban flooding, Alignment, Slope

1.INTRODUCTION

Urban flooding occurs when the capacity of the storm drainage system is exceeded by high-intensity rainfall, leading to inundation of the urban area with a significant amount of runoff. The reduction of vegetation cover and increase in impervious surfaces due to developmental activities in urban areas locally intensify the runoff. However, the present stormwater drainage system is inadequate in managing the impact of runoff generated as a result of changes in land use. This results in extreme flooding in urbanized areas during intense storms (Pour et al., 2020). Urban development also disrupts the natural drainage pattern by transforming the natural landscape, leading to the substitution of the gradual accumulation of rainwater through an overland flow to a local stream network with a graded land surface. In this graded land surface, the flow is carried by streets (Bisht et al., 2016).

Urban flooding is a significant global challenge that poses severe threats to urban infrastructure and results in substantial losses. In some flooded cities, water depths generally range between 50-70 cm (Mark et al., 2004). Although casualties due to urban inundation are not high, the high population density and property values make urban floods more adverse in nature (Pour et al., 2020). South-East Asian cities are particularly vulnerable to frequent and severe urban flooding due to the low standard of drainage systems and intense local rainfall. As developing cities continue to grow rapidly without adequate budgets to improve and extend existing drainage systems, the situation is likely to worsen (Mark et al., 2004).

With the rapid expansion of development activities in Bhutan's capital city of Thimphu, acute problems of stormwater drainage have arisen during the early stages of development. This problem has been exacerbated in recent times, mainly during monsoon seasons. Local residents in urban areas attribute the drainage failure to poor condition and inadequate capacity (Dorji, 2014). Studies conducted through questionnaire surveys identified blockage due to solid waste, inadequate storm drainage capacity, and a poor storm drainage network as causes of drainage problems (Dema et al., 2018). In May 2020, shops located in the basement of Norling Building were flooded when nearby stormwater drainage became clogged following an extreme rainfall event. This highlights the need to investigate the causes and factors contributing to urban flooding in the capital city.

2. Aims and Objective

The primary objective of this research is to investigate the factors responsible for urban flooding in the Norzin area of Thimphu city by utilizing SWMM software. The study adopts the following objectives:

Develop urban flooding scenarios using SWMM to identify the most severely affected area.

Validate the results obtained by comparing them with actual flooding events.

Analyze the factors that contribute to flooding, such as drainage capacity, alignment, slope, and blockage.

Determine the major factors that contribute to urban flooding in the study area.

3. Methodology

3.1 Study Area

The city of Thimphu covers a total area of 26 square kilometers, stretching from Dechencholing in the north to Babesa in the south. The study is focused on the central area of the city, which covers 2.26 square kilometers and is most affected by urban flooding. These flood-prone areas have been validated by past flooding events reported in newspapers and online news sources. The study area includes Norzin lam, Centenary Farmers Market, Changlimithang area, and the primary storm drainage near the National Memorial Chhorten, as well as their tributary storm drainage covering Mothithang area, as illustrated in Figure 1. Thimphu is located in the western central part of Bhutan, between 27°28'00"N, 89°38'30"E and 27°28'00"N, 89°38'30"E, with an altitude ranging from 2257 meters to 2750 meters above sea level.

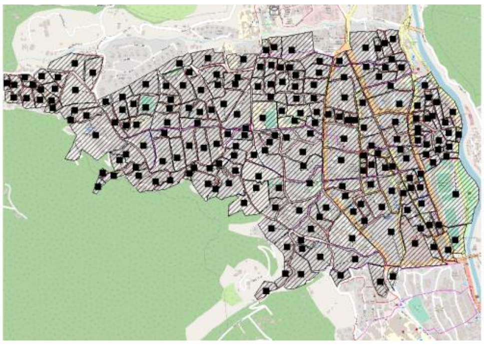

Figure 1: Study area showing

3.2 Data Collection

In order to model the Thimphu city using the Storm Water Management Model (SWMM), it is imperative to gather pertinent input data. This includes acquiring the layout of the stormwater drainage system, identifying the soil type, and obtaining Digital Elevation Model (DEM) and rainfall data. The soil type is crucial in determining the curve number in the Soil Conservation Service (SCS) Curve Number (CN) method of infiltration. Based on the soil survey conducted in 1997 by the Royal Government of Bhutan's Renewable Natural Resources-Research Centre (RNR-RC) in Yusipang, the soil in Thimphu is classified as sandy loam and sandy clay loam. The stormwater drainage information for the entire Thimphu city was procured from the National Land Commission Secretariat (NLCS). A high-resolution, terrain-corrected ALOS DEM with a resolution of 12.5 meters was obtained from the Alaska Satellite Facility (ASF). The National Center for Meteorology and Hydrology (NCHM) provided rainfall data in 15-minute intervals for the years 2017 to 2019.

3.3 Parameter Selection

The evaluation of a stormwater drainage system requires a systematic analysis of various factors that can lead to urban flooding. These factors should have a significant impact on the drainage system during a flooding event. S. Mohammadiun, in a study published in 2018, highlighted that urban flooding can occur due to a variety of unfavorable circumstances. These situations can include scenarios where the capacity of the storm drainage system is exceeded or when blockages occur in densely populated areas (Mohammadiun et al., 2018). Therefore, any assessment of a stormwater drainage system must consider such critical factors that can lead to urban flooding.

Thus, this study aims to investigate the causes of urban flooding in the Nor-zin area of Thimphu city by considering two primary factors: the capacity of the storm drainage system and blockages in the conduit. These factors are influenced by external factors such as heavy rainfall and urban litter (e.g., trash, debris, or pollutants) as noted by Armitage (2007). However, internal factors such as obstructive flow alignment of storm drainage, improper slope maintenance, and structural failures of the drainage can also contribute to urban flooding. Therefore, to account for an internal factor, this study will analyze the alignment and slope of the drainage system as an additional governing factor that contributes to urban flooding in the Norzin area.

3.4 SWMM Modeling

In this study, the urban catchment of the Norzin area was modeled using the Environmental Protection Agency Storm Water Management Model (EPA SWMM). This model is a dynamic simulation tool that can simulate runoff generated from rainfall, accounting for both quality and quantity, in both single and long-duration events (Rossman et al., 2010). For the purpose of simulating the issues faced by the storm drainage system in the Norzin area, a single event simulation was employed.

In addition, the routing model used in the simulation can be based on three options: steady flow, kinematic wave, and dynamic wave. However, for this project, steady and kinematic wave routing approaches were considered too simplified and unable to account for backwater effect, pressurized flow, flow reversal, and non-dendritic layouts. As such, dynamic wave routing was chosen due to its ability to handle all of these phenomena and its complexity being suitable for the nature of the project.

To simulate extreme rainfall events that can occur in a year, three separate daily rainfall events were selected and introduced into the hydrological model of the Norzin area, with a recording interval of 15 minutes between each event. The extreme rainfall events from the Kuzhugchen station in 2017, 2018, and 2019 were chosen to be the precipitation input for the catchment model.

3.4.1 Subcatchment Property Modeling

In order to compute surface runoff in the study area, the catchment was divided into 211 urban sub-catchments, based on field data. Each sub-catchment was modeled in terms of its area, width, terrain slope, percentage of impervious area, Manning's n number for pervious and impervious areas, and infiltration. The area of each sub-catchment was automatically generated in SWMM once it was mapped, and the characteristics of each sub-catchment heavily influence the amount of runoff generated. Larger areas receive more precipitation, which can subsequently result in more surface runoff.

To ensure accuracy, the sub-catchment areas were verified in QGIS after manually mapping them out and geo-referencing the SWMM base map. Using the field calculator features in QGIS, the area of each sub-catchment was extracted. Then, the width of each sub-catchment was calculated using Eq. 1.

$$W = \sqrt{A}$$

Where W is the width of subcatchment (m) and A is the area of subcatchment (m2). The parameter of width governs the concentration time and shape of hydrograph (Babaei et al., 2018).

To calculate the slope of each subcatchment, the elevation data was extracted from the DEM of the study area using QGIS. The maximum and minimum elevations of each subcatchment were then determined, and the slope was calculated using the following equation:

Slope = (Max. Elevation - Min. Elevation) / Catchment Length

where the catchment length is the width of the subcatchment calculated earlier. The slope of the terrain is an important parameter in determining the surface runoff generated by each subcatchment, as steeper slopes tend to produce more runoff than flatter ones.

The study area includes heavily paved terrain, roofs, and highways where rainfall cannot penetrate, resulting in a percentage of impervious area assumed to be 100%. The manning's roughness coefficient n for smooth concrete (0.013) and short prairie grass (0.15) were assigned to each subcatchment, depending on the nature of the pervious and impervious area. Each subcatchment is associated with numerous parameters, and this stage of modeling can be time-consuming and require a significant amount of effort. To accelerate the modeling of parameters, the open-source tool OSTRICH-SWMM can be used, which is used for calibrating these parameters (Behrouz et al., 2020).

The infiltration rate is influenced by the specific methodology employed and the variables considered within that methodology. In this study, the Soil Conservation Service (SCS) curve number (CN) method was utilized, incorporating parameters such as soil group type, curve number, saturated conductivity, and drying time. The conductivity value is contingent upon the soil group type, with the Thimphu region classified as loamy sand or sandy loam, presenting a moderately low to moderately high runoff potential and saturated conductivity range of 1.42 to 0.06 inches per hour, according to the Hydrology National Engineering Handbook. The drying time of the urban catchment area corresponds to the duration required for fully saturated soil to reach complete dryness, which was assumed to be 7 days for modeling purposes.

3.4.2 Stormwater drainage Modeling

The process of modeling stormwater drainage primarily involves the representation of conduits and junctions. Conduits can be modeled by taking into account various parameters such as flow path, cross-sectional area (shape geometry), elevation above the inlet or outlet, conduit length, Manning's roughness coefficient, and whether they are open or closed (Rossman et al., 2010). In SWMM, the flow rate is determined using Manning's equation.

$$Q = 1/n\ AR^{(2/3)}S^{(1/2)}$$

Where Q is the flow rate, A is the cross- sectional area, R is the hydraulic radius, S is the slope and n is the Manning's roughness co-efficient.

To determine the flow path of the current stormwater drainage system in the Norzin area, the primary and secondary drainage plan map obtained from the National Land Commission Secretariat (NLCS) was overlaid onto the study area map. Subsequently, a map was generated in QGIS, including a world coordinates file, to serve as a backdrop for mapping the stormwater drainage system in SWMM. This map is a composite of the open street map of the study area and the stormwater drainage system.

Following the creation of the SWMM backdrop, the conduit mapping phase commences with the introduction of junctions. These junctions serve as endpoints for conduit sections and represent drainage system nodes, which physically correspond to manholes in sewer systems or pipe connection fittings (Rossman et al., 2010). Modeling the junctions in the Norzin SWMM involves determining their invert elevation and height to ground surface. The invert elevation of the junction was obtained from the terrain-corrected ALOS PALSAR digital elevation model (DEM), while the height to ground surface parameter was assigned based on the depth of conduits linked to the junctions.

Continuing with the conduit mapping, conduits were delineated between the junctions, using the QGIS-generated backdrop. The nature of the conduit's roughness is a crucial factor in flow routing, and different Manning's roughness coefficients are assigned to the conduits based on their construction materials. Conduits primarily made of concrete were assigned a roughness coefficient of 0.02. The conduits varied in shape, including trapezoidal, rectangular, and L-shaped. Trapezoidal-shaped conduits were used for primary drainage, while rectangular-shaped conduits were used for secondary drainage. Once conduit mapping was complete, to investigate the impact of blockages, weirs were introduced at 10 potential garbage/blockage collection points in the study area. The weirs were modeled as transverse weirs with a vertical height of 0.25m at the weir opening, accounting for 25% blockage in 1m depth primary drainage. The horizontal length of the weir crest was equal to the width of the primary drainage. The discharge coefficient for the transverse weir was set to 1.605 CMS. These weirs were examined in the context of the blockage factor.

4. Result and Discussion

A total of six simulations were conducted in the project, comprising three simulations each for two different scenarios. The first scenario involved simulations without blockage. Three simulations were performed for the years 2017, 2018, and 2019 using the high-intensity rainfall data for each respective year. Analysis of these simulations revealed that 47 junctions experienced flooding in 2017, 46 in 2018, and 49 in 2019. The frequency of flooding for each junction was calculated from these simulations. Junctions that flooded in all three simulations were classified as high-risk locations, those that flooded twice were classified as medium-risk locations, and those that flooded once were classified as low-risk locations. The flooding patterns of these junctions were analyzed, and they were classified based on the factors that contributed to urban flooding events.

The urban flooding classifications are based on factors such as capacity, alignment, slope, and blockage. The slope factor was further subdivided into elevation, ponding, and slope to address specific issues faced by different drainage sections. The figure below illustrates the classification of flooding junctions based on the factors that contribute to urban flooding.

Table 1: Junctions were influenced due to which factor causing urban flooding in respective years.

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

The second situation pertains to the simulation where potential blockage points were identified for the purpose of modelling. Three simulations were conducted for the same rainfall intensity and duration. In this scenario, a new factor that influences urban flooding, i.e., blockage, was introduced. The pie chart in Figure 2 provided below represent the number of flooded junctions for each year.

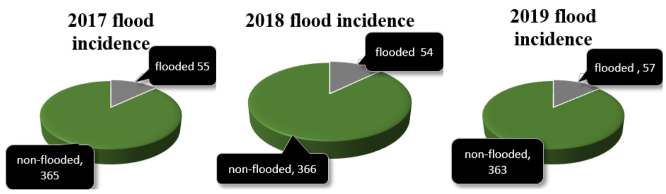

Figure 2: Number of flooded junctions

Table -2: shows what number of junctions that were influenced by which factors.

The findings of the study revealed that alignment and slope emerged as the primary factors responsible for urban flooding, with a dominant contribution of 72.29%. These factors can be further classified into elevation,

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/slope	4	4	5
Blockage	7	7	7

ponding, slope, and alignment. The secondary factor contributing to urban flooding was blockage, accounting for 12.65% of the total observed flood events.

Table -3: Percentage of influence the factors under study caused urban flooding.

Year	Capacity	Alignment/Slope	Blockage	Capacity/Alignment
2017	7.27	72.72	12.72	7.27
2018	7.40	72.22	12.96	7.27
2019	7.01	71.92	12.28	8.77
Grand %	7.23	72.29	12.65	7.82

4.1 Capacity Analysis

Two scenarios were analyzed to determine the capacity of the drainage system. The first scenario involved the simulation without blockage, and the results indicated that a total of 4 junctions out of the 416 experienced failure due to insufficient capacity. The failure occurred immediately after the storm reached its maximum intensity, which was 26mm/hour, 39.2mm/hour, and 30mm/hour for 2017, 2018, and 2019, respectively. These flooded junctions were primarily located at the intersection points where multiple drainage systems converge.

The simulation in which weirs were introduced had four junctions out of the 420 that flooded due to capacity in all three rainfall events, as shown in Figure. 3. The same result in both simulations helps us understand that the points where weirs were incorporated did not influence the overall events of capacity failure. Therefore, at this point in time, the capacity of the stormwater drainage is sufficient. However, with the passage of time and the onset of urbanization and climate change, the capacity of drainage will need revision (Berggren et al., 2014). At that point, when the current stormwater drainage system becomes obsolete and inadequate in terms of capacity, an expansion and redesign will be inevitable (Dema et al., 2018).

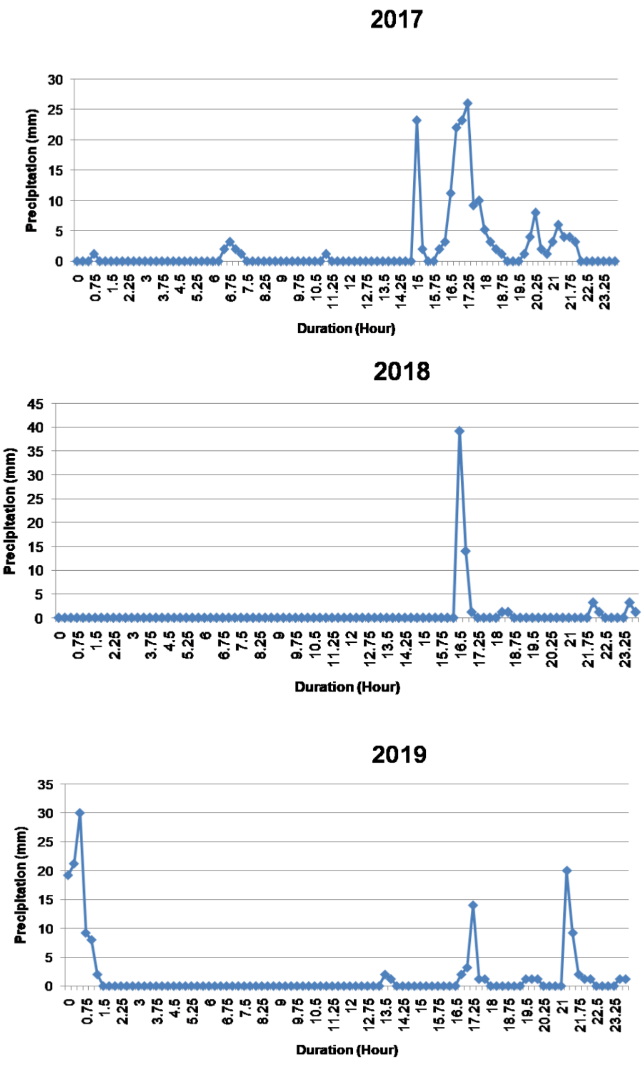

Figure 3. Rainfall events selected for modelling.

4.2 Alignment and Slope

The causes of urban flooding related to alignment and slope are further subdivided into six categories: 1) elevation, 2) alignment, 3) ponding, 4) slope, 5) combined alignment and slope, and 6) combined alignment and capacity, to provide a more detailed understanding of the factors involved.

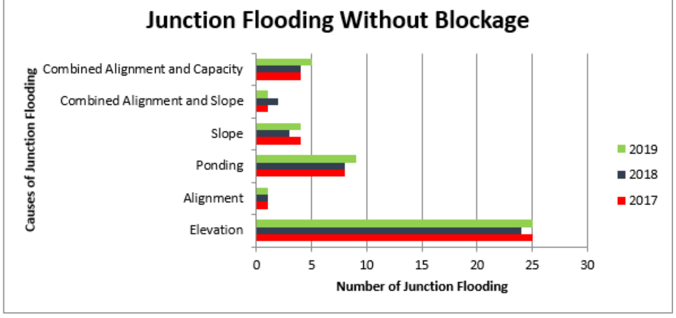

Figure 4: Junction flooding analysis considering various factors in the absence of channel blockages

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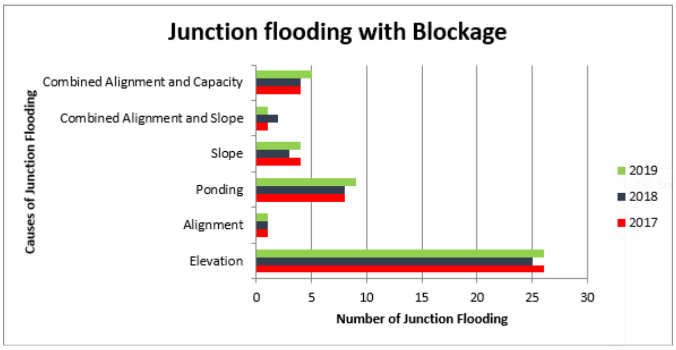

Figure 5: Junction flooding analysis considering various factors considering channel blockages

The above bar chart (Fig. 4 and Fig. 5) provides a visual representation of the number of flooded junctions in 2017, 2018, and 2019 and the corresponding causes of flooding. Among the factors analyzed, Alignment and Slope, specifically the sub-factor of Elevation, was identified as the primary cause of urban flooding, with 25 flooded junctions. This was followed by Ponding, with 8 flooded junctions. Introducing blockage did not result in any changes to the parameters of junction flooding, except for the number of flooded junctions due to Elevation, which increased by one. Some of the discussions related to the factors of Alignment and Slope are as follows.

The slope of most storm drains in Thimphu city, which slopes towards the Wangchhu river, does not pose any problems as the stormwater flows under the influence of gravity without much difficulty. However, in areas where the drainage system encountered issues due to slope, it was observed that most drains were constructed solely to fulfill the rules of constructing a drain near each household or to provide an L-shaped drain near the roads, without considering the slope aspect and the need for water to be discharged at the outlet. This was evident from the fact that the failure of drains shown by the simulation in SWMM was comparable to the real-life scenarios in Thimphu city, where the drains were filled with stormwater even during dry days.

Some urban floods were also caused by stormwater flowing down steep slopes and then transitioning to a gentler slope (represented in the bar graph by combined alignment and slope). The spillage of the stormwater occurred during this slope transition due to the supercritical flow condition of the stormwater.

The plan of Thimphu's stormwater drainage presents a clear picture of the alignment problems that plague the city's drainage system. The construction of drainage during the early days of urbanization in Thimphu was carried out haphazardly, without proper consideration for alignment. In most places where stormwater from different regions intersected, the drains were connected directly at a 90-degree angle, causing the stormwater to spill over the drains.

Urban flooding caused by ponding in Thimphu was mostly due to stormwater being unable to flow through adjacent conduits, as the water had to flow upward. This condition resulted in stagnant water in certain locations, leading to overflow on the sides of the drains. In some cases, ponding was caused by water from impervious catchments, such as roads and footpaths, being unable to drain into the storm drains. Urban flooding caused by elevation was similar to ponding, except that, in the case of elevation, the stormwater was forced to backflow due to having to travel at a higher elevation in adjacent conduits. The backflow of water also resulted in urban flooding.

4.3 Blockage

Blockage failure refers to a situation in which garbage or litter obstructs the flow path, resulting in lower discharge values and increasing the water level upstream. This situation is particularly unfavorable, given that greater blockages can result in a complete obstruction of the flow path, causing flooding in the upstream section of the storm-water drainage system. Due to drain blockage, water stagnation occurs in the lower elevation area of the drainage system, and during high-intensity rainfall, there is obstruction to the flow of discharge causing overflowing to the rest of the drainage system (Chandrasena et al., 2017). Analysis conducted from three rainfall events shows that the introduction of weirs at specific locations resulted in a decrease in flow rate from an average value of 0.702 CMS to 0.425 CMS. This subsequent decrease in flow rate results in an increase in the depth of flow in the upstream section, causing higher chances of flooding. For the study, ten locations were identified as potential points for garbage collection in the stormwater drainage system.

Thimphu is a common sight of clogged drains and flooded roads during monsoons (Kuensel, 2020). The three simulation results show that blockage contributed around 12.66% to the overall flooding scenario. The simulation results show even higher projections if more potential blockage points are recognized. Individually examining blockage, out of the 10 potential blockage points, 7 points experienced urban flooding due to blockage in each simulation result shown in Table 4, which is 70% of the total blockage points. This interprets to a 70% probability of a potential blockage point to flood. The blockage causes can also be due to the fact that residents have been irresponsible in waste disposal. Therefore, providing covered drainage will help reduce the blockage of conduits, and a daily cleaning routine of the storm drainage will help decrease urban flooding. Moreover, on a probabilistic approach, experimental results on Monte Carlo simulation prove to be more efficient and cost-effective than the hydraulic approach stated by Jafar (Yazdi, 2018). This probabilistic approach can be the next step in solving 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

5. CONCLUSION

Thimphu's rapid urbanization has led to increased runoff due to the conversion of pervious areas to impervious areas through the construction of concrete surfaces. The lack of infiltration on these surfaces results in the precipitation remaining on the surface and generating runoff, which overwhelms the capacity of the stormwater drainage system. This is due to factors such as carrying capacity, alignment, slope, ponding, elevation, and blockage of the system. These factors were grouped into capacity, blockage, and alignment and slopes, where alignment of slopes comprises sub-factors like ponding and elevation. The simulation results showed that alignment and slope were the primary factors contributing to urban flooding in Thimphu city, accounting for 72.29% of urban flooding. The sub-factor of elevation from the main factor of alignment and slope caused the highest number of flooding.

Through area investigation, 10 potential blockage points were identified, with 7 of them experiencing flooding, accounting for 70% blockage failure of junctions where potential blockages were introduced. If new potential blockage points were identified in the future, each of the new potential blockage junctions has a 70% probability of flooding. An average of 7.23% of the junctions that experienced urban flooding were caused by the factor of capacity, accounting for 4 flooded junctions per simulation. To address these issues, implementing covered drainage systems and conducting daily cleaning routines of the storm drainage system can help reduce blockage and decrease urban flooding. Additionally, using the probabilistic approach from experimental results on Monte Carlo simulation can be more cost-effective and efficient in solving the blockage problem.

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