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Application of LID techniques as mitigation measures for urban flood using SWMM

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Abstract

Urbanization and increased imperviousness are the main causes of the inadequacy of the existing drainage system, while unplanned waste disposal and poor maintenance are further issues. The Pulbazar Area of Banepa is flooded every monsoon season, turning the Araniko highway into a stream, impacting transportation and the daily lives of the residents. The natural drainage surface is being impacted by the haphazard growth of urban areas. The Storm Water Management Model (SWMM) is one of the most popular and worldwide utilized urban flood design and management models for modeling urban flooding. In addition, it is utilized for modeling non-point source pollution, reducing combined sewer overflow, planning, evaluation, and design associated to rainfall runoff, combined and sanitary sewage, and other drainage systems. For this study, SWMM 5.2 was used. The primary goal of the research is to study the hydrological and hydraulic status of the urban storm water sewerage as well as drainage system and evaluate the application of Low Impact Development (LID) for reducing runoff volume, conduit velocity and flooded nodes in the study area. The LID practices which were modelled were Permeable Pavements and Green Roofs. From the result obtained, it can be concluded that LID applications like Permeable pavements and green roofs can reduce the runoff by 28% and 72% respectively in the fast urbanizing and congested cities like Banepa.

Keywords

SWMM, Urban Flooding, Low Impact Development, LID, Permeable Pavement, Green roof, Storm water Management, Pulbazar,Banepa

1. Introduction

Nepal is one of the ten fastest urbanizing countries in the world. Nepal's towns and rural areas are becoming more urbanized at a rate of 5 to 7 percent every year. More land must be developed from its natural state as more people choose to live in cities. More than half of the world's population now resides in cities, a first in human history. By the end of 2050, this is anticipated to rise to 70%. Natural drainage is impacted by the current trend of haphazard migration and rapid, unplanned urbanization, which ultimately increases the pressure on roadside drains [1]. As Banepa is the business central area of the Kavre district, there is haphazard construction of buildings, pavements, and concrete structures. The greenery and cultivable lands have been transformed into impervious areas with rigid surfaces. Every year mostly during monsoon season, Banepa faces flash flood in the Pulbazar area and Dhaneswore area. As the stormwater cannot drain out through the present drainage system, it overflows into the roads creating a pond on the highway. As Pulbazar lies on Araniko Highway, it disrupts the traffic and hampers the people who travel daily for study, work, and other purposes.

More roofs and other sealed surfaces are frequently a result of urban densification, which reduces the opportunity for water to collect and enter surfaces. Just as in another urban area, Banepa also has the same scenario. The land which was covered with greenery and cultivable lands is now changed to an impervious area with the addition of buildings and a rigid surface. In addition to extreme weather events, rapid urbanization and improperly constructed or planned sewers are thought to be the most significant contributors to the rising number of urban flood disasters. [2]. Figure 1 and 2 shows how urbanization has increased from 2012 to 2022 in the Pulbazar area of Banepa.

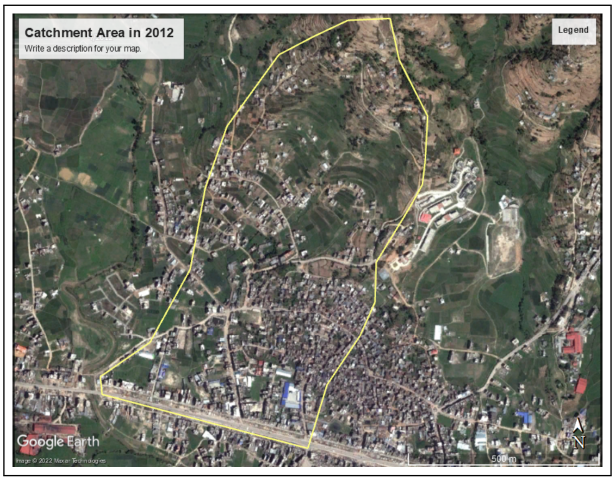

Figure 1: Catchment area, 2012 (Source: Google Earth)

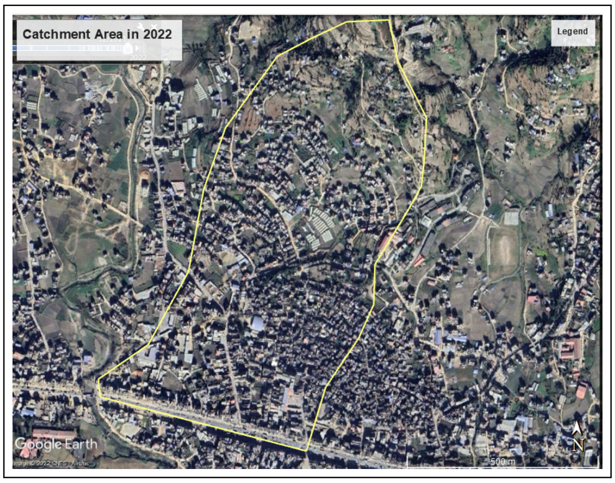

Figure 2: Catchment area, 2022 (Source: Google Earth)

Many people who live by the roadside must deal with significant property damage and daily challenges during the monsoon season. It has an impact on their emotional health in addition to the loss of their material possessions. Extreme rain and flooding in cities come with a high societal cost, including traffic jams, structural damage to buildings and infrastructure, people living in fear of future floods, health degradation due to contaminated water, lost sales for businesses, contamination of drinking water, and local beneficiaries [3].

To manage urban flooding effectively, it is necessary to simulate and anticipate the flooding phenomena caused by several influencing elements. Given the complexity of the issue, numerical modeling coupled with geographical methods (such as remote sensing and geographic information systems (GIS)) are necessary for simulation[4].

The LID (Low Impact Development) is an alternative, environmentally responsible design method that imitates how natural areas store and infiltrate rainwater. By decentralizing stormwater management and absorbing rainfall across the landscape, the LID approach safeguards local and regional water quality. A green roof primarily prevents runoff from impervious surfaces by retaining some of the rainfall while also lengthening flow paths. Permeable pavement has high porosity and perviousness, influencing the local hydrology where it is planted. Pavements made of impervious concrete or asphalt that cover sidewalks, parking lots, secondary roads, etc. can be replaced with Pervious pavement [5]. From the research of [6], he found that porous pavement has a great ability to improve the infiltration of stormwater runoff. In a variety of climates, green roofs have been shown to retain a sizable portion of rainfall (on average 63%). Research has also demonstrated that bio-retention and pervious pavements continue to infiltrate even when there is frost on the ground, contrary to popular belief.

There are numerous open-source software tools that can effectively model urban flood scenarios in a catchment, including the Hydrologic Engineering Centers-River Analysis System (HEC-RAS), Storm Water Management Model (SWMM), Hydrologic Engineering Centers-Hydrologic Modeling System (HEC-HMS), MIKE URBAN and MIKE FLOOD. SWMM is freely available latest and regularly updated software whereas HYKAS software is paid one. Because SWMM has simple steps, anyone can easily learn from various sources and design the size of the drain. SWMM would be a more appropriate model in the context of Nepal due to its ease of access; simple data input parameters; and simple processing steps, as opposed to other costly and complicated models. [1]. With the help of a series of non-linear reservoirs, a dynamic wave equation, and land surface components, SWMM simulates infiltration and runoff from the sub catchment. Various options for modelling infiltration is available in SWMM among with Horton's Equation is one of the most frequently used model.

$$f_p(t) = f_c + (f_o - f_c) * e^{-kt} \quad (1)$$

where,

$f_p(t)$= infiltration capacity at any time (t) from the start of the rainfall

f_o= initial infiltration capacity a time (t) = 0

f_c= final steady state infiltration capacity at t = t_c

k = Horton's decay coefficient which depends upon soil characteristics and vegetation cover.

SWMM has also been applied to non-point source pollution modeling, floodplain mapping, reducing combined sewer overflow, flood control drainage systems and, detention facilities.

[7] in his research about performance review and gap analysis of SWMM model did the gap analysis in the model's capacity to simulate water quality while taking into account the effectiveness of green infrastructure (GI) and low impact development (LID) designs and concluded that SWMM is a suitable model for large- and moderate hydro-logical applications because the degree of detail underlying the conceptual design and its overall computational parsimony are well balanced.

1.1 Study Area

Banepa is a historic town and municipality located approximately 1500m (4900ft) above sea level. It is located in Bagmati Province, about 25 kilometers east of Kathmandu. Geographically, the Banepa municipality's boundaries are the districts of Mandandeupur, Dhulikhel, Panauti, and Bhaktapur, which are located between 27° 37'01" and 27° 39'03" north latitude and 85° 30'45" and 85° 32'52" east longitude. It covers an area of 5.56 sq. km. where total population is 67,629 (2021 A.D) i.e., 12,163 people are living per sq. km. There are 14 wards in Banepa Municipality. The town has a long history of serving as a hub for trade between Nepal and Tibet. The main river tributaries of this area is Punyamata Khola and Roshi Khola. The Punyamata river extends from Nala to Khadpu and flooding from this river frequently occurs in Pulbazar Area and Khadpu Area. Maps of flood inundation over the ten-year return period (RP) indicate that substantial flooding affects 50.17 hectares of land in Banepa [8]. From the data collected from Climate-data.org, the average annual temperature of Banepa is 16.2º c and about 2596 mm of precipitation falls annually. The maximum amount of rainfall occurs in July with an average of 714mm of precipitation.

As the Pulbazar area lies on Araniko Highway, it seems to be of main concern, causing traffic congestion, property loss, and hampering the business in the core area. Topographically this area has depression which is also one of the reasons for flash floods. The outlet is slightly at a higher elevation than the preceding node. As seen in the section from google earth in Figure 3, the Outlet lies at a higher elevation than Node J06, so water cannot drain out easily as there isn't any pressurized flow. Some of the other possible causes of flooding in this area are:

- Insufficient drainage size
- River encroachment reducing the size of waterway
- Sediments deposition in the river basin
- No cleaning and maintenance of existing drainage lines

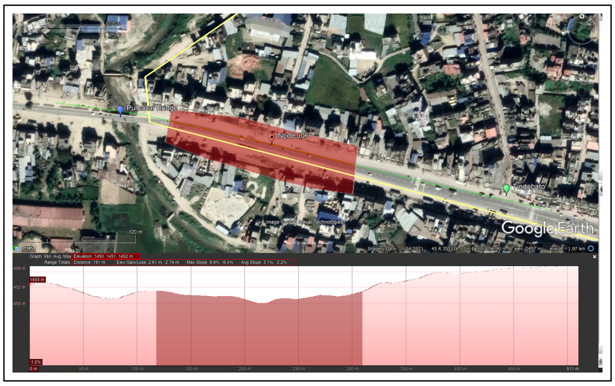

Figure 3: Profile section of inundation area

Figure 4: Flooding at Pulbazar

2. Methodology

First of all, the extent of the study area was fixed by calculating the catchment area of the Pulbazar inundation area using QGIS and Grass GIS. Then the catchment area was further divided into 11 sub-catchment areas based on elevation and existing drainage networks. The catchment has highest elevation level of 1590m and lowest elevation of 1492m with a total area of 51.28 Ha. All the input parameters were determined by primary and secondary sources. The coordinates and depth of nodes and the size of drainage networks were determined through a site survey. The rainfall data were collected from DHM for 10 years duration (2011 to 2021). Then rainfall intensity was calculated for various return periods of 2, 5, 10, 50, 100, 200, 500, & 1000 years.

2.1 Rainfall Data Analysis

As there wasn't any rain gauge station in the study area, rainfall data was collected for 4 nearby stations which were: Nagarkot, Khopasi, Panchkhal, and Godavari. By using Theissen Polygon, it was found that Nagarkot Rain gauge weights 95% and Khopasi Rain Guage weights 5% in the study area.

Figure 5: Site Survey for Drainage sizes and node invert elevations

Figure 6: Site Survey for Nodes surface elevation

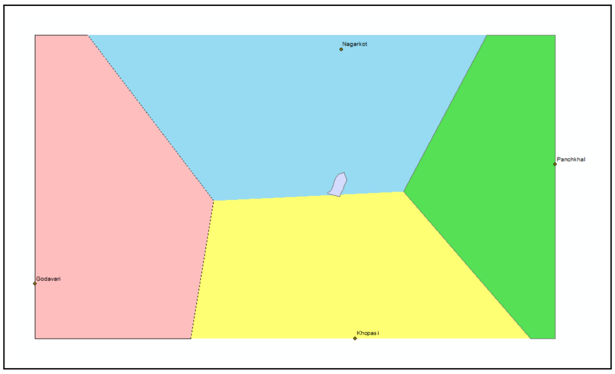

Figure 7: Theissen Polygon method

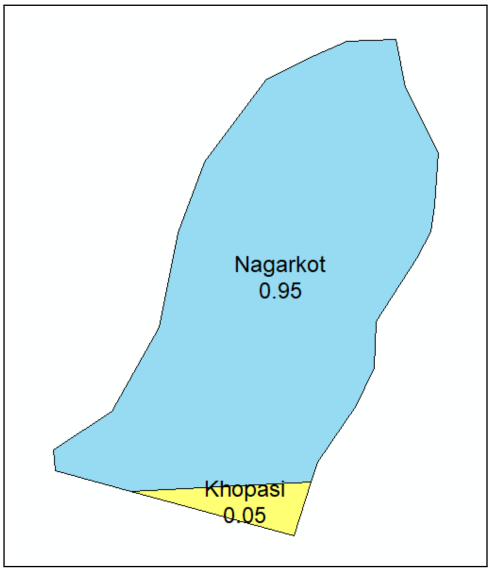

Figure 8: Catchment area showing weighatge to Nagarkot and Khopasi Rain Gauge Stations

The data obtained from DHM was only available on daily basis, so it was necessary to disaggregate that daily rainfall value into short-duration rainfall like 5mins, 10mins, 30mins, and 1hr. For this purpose, empirical reduction equation (1) developed by Indian Metrological Department (IMD) is used [9].

$$P_t = P_{24} * (t/24)^{1/3} \qquad (2)$$

Where, P_t is the required rainfall depth in mm

P_{24} is the maximum daily rainfall in mm

t is the time duration of which the rainfall is required in hours

Now, using the Gumbel Theory of distribution, rainfall intensity was determined for the different return periods. IDF curve was also generated through these data which is shown in Figure7. The Gumbel method is an uncomplicated strategy that can be used in extreme occurrences (maximum value or peak rainfalls), as [10] noted . It is the most widely used distribution method for Intensity duration frequency analysis and flood probability analysis.

$$P_T = P_{avg} + K_T * S \qquad (3)$$

Where,P_T is the rainfall for return period T

P_{avg} is the average of maximum daily rainfall in observed years

S is the standard deviation of maximum daily rainfall in observed years

$$K_T = -(6^{0.5}/\pi) * (0.5772 + ln \ln(ln(T/(T-1)))$$

is the Gumbel frequency factor

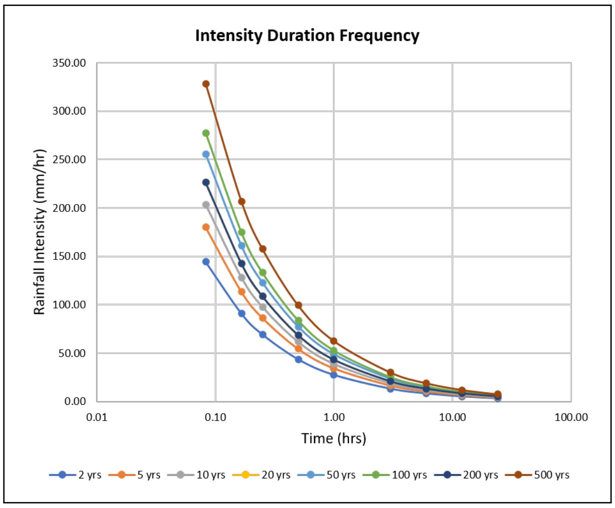

Figure 9: IDF Curve

2.2 LULC Map

A Land Use Land Cover change map was generated to determine the imperviousness of each sub-catchment. For this, Sentinel-2 data for the year 2022 was used which was downloaded from open source USGS Earth Explorer. The LULC map of the catchment area is shown in Figure 8. The study area covers 67.77% of the built-up area, 16.19% of vegetation area, and 16.15% of barren land. The impervious area and slope of each sub-catchment were determined using the map and QGIS and their values are shown in Table 1.

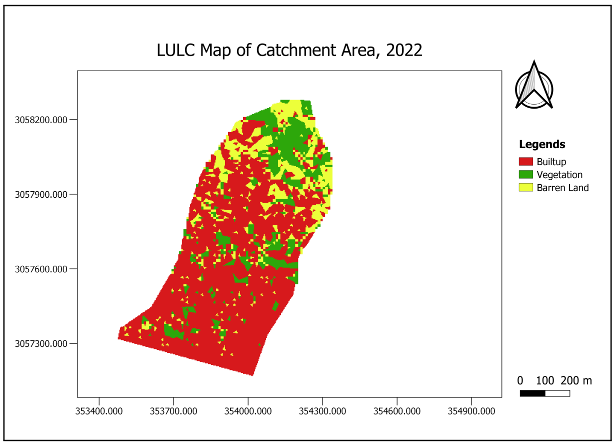

Figure 10: LULC Map of catchment area, 2022

Table 1: Impervious area and slope of sub basins

Sub basin	% Imperv Area	%Slope
B01	16.46	29.07
B02	70.41	13.17
B03	73.10	9.03
B04	83.77	12.51
B05	86.51	5.39
B06	85.99	4.30
B07	31.98	23.00
B08	63.44	14.92
B09	73.32	12.79
B10	95.66	7.42
B11	91.74	6.06

2.3 Modelling and Simulation

After all the required input parameters were determined, modeling was done in SWMM. First of all, the Backdrop image was added and it was georeferenced according to its coordinates. Sub catchment areas were drawn and nodes for each sub-catchment area were placed along with its coordinates and inverted elevation. Conduits connecting the nodes were drawn along with their properties and an outlet was placed on the side of the bridge at the Pulbazar. The input parameters for conduits, were: drainage network dimension, Manning's roughness coefficient, for junctions were: elevation and the maximum depth, and for outfalls were: invert elevation and the maximum depth of drains. The elevation of the node and outfall were obtained from Google Earth. The max depth for the nodes was kept at 1.5m and the Manning's roughness coefficient was kept at 0.015 for the concrete conduit. The run-off from the corresponding sub- catchments was distributed to the respective nodes and finally to the outlet through conduits. For rainfall data, time series data was added manually at an interval of 15min considering rainfall duration of one hour for a Return Period of 100 years.

2.4 LID Practices

There are various LID controls available in the SWMM model under the hydrological category; rain barrel, bio-retention cells, vegetation swale, permeable pavement, green roof, infiltration trench, etc. Among these, the most favorable control for Banepa was permeable pavement and green roof.

Permeable Pavement In the LID module of SWMM, a permeable pavement system is represented by a combination of three vertical layers (i.e., the surface, pavement, and storage layers) and an optional underdrain [12]. A permeable pavement system with an underdrain is described by a total of 16 parameters in the LID module. In addition to these 16 parameters, the simulations also need to account for the area, width, and ET rates of the permeable pavement system as well as the infiltration parameters of the underlying native subsoils [11]. The impervious roads which were present in secondary roads, sidewalks, parking areas, etc were replaced by permeable pavement. The area of roads present in each sub-catchment was calculated using google earth pro and QGIS. The area that must be converted to permeable pavement was estimated at 0.086 sqkm which is about 16.8% of the total catchment area.

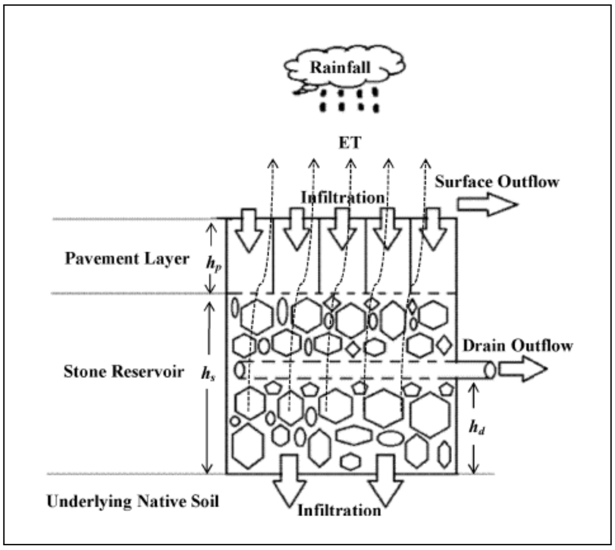

Figure 11: Permeable Pavement mechanism, source [11]

Green Roof Green roofs usually contain a liner, insulation, drainage system, planting medium, and low-maintenance, drought-tolerant plants that reduce runoff by holding back and slowing down water that would otherwise flow into the storm drains. In addition to storm water management, green roofs can reduce the cost associated with energy usage and improve the air quality of the surrounding. To balance the load-bearing capacity of the building's roof, the choice of a vegetated system must be appropriate. Drainage paths provide a way for excess water to reach rainwater drainage devices. The filter prevents any material from clogging between the growing medium and the drainage layer. For modeling Green Roof, the LID control editor uses various parameters under the subtopics of surface, soil, and drainage mat. The values like berm height at the surface and the thickness of soil and drainage mat were entered while other values were chosen referring to the ranges mentioned in the manual of SWMM. Google Earth and Open Street Map (OSM) from QGIS were used to

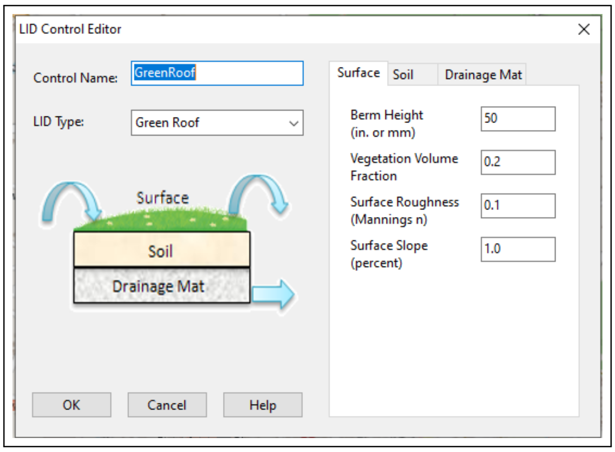

Figure 12: Green roof editor control showing surface parameters

calculate the total area of the roof that could be converted to a green roof. Most of the roofs in the study area were flat roofs, which is a useful space for various purposes. As converting all the roof space into a green area might not be possible in the real scenario so simulation was done for two different cases: ie i) considering all the rooftop converted to vegetation (100% green roof) and ii) considering only half area of roof converted to vegetation (50% green roof)

3. Result and Discussion

3.1 Analyzing Longitudinal profile

Profile plots give a helpful graphical outline of the information which is one of the effective data analysis techniques. For this study area, there are two major drainage profiles. One from Node J01 to OutO1 and the other from Node J07 to OutO1. The Water Elevation Profile for both during peak flow at 1:15 hours considering time series data of 1-hour rainfall duration of 100 years return period are shown in Figures 11 & 12.

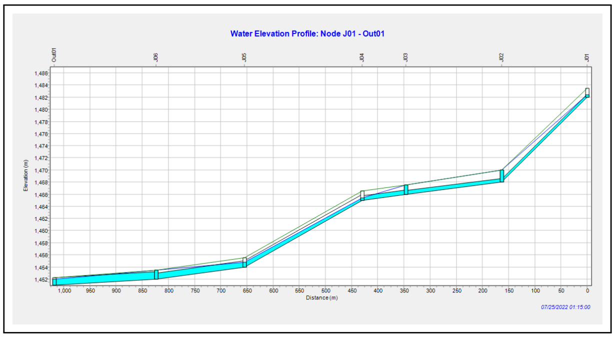

Figure 13: Water Elevation Profile from Node J01 to Outlet OutO1

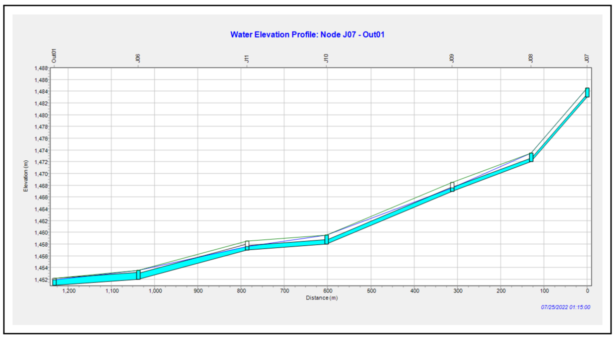

Figure 14: Water Elevation Profile from Node J07 to Outlet OutO1

3.2 Analyzing Sub catchment, Node, and Link Properties

Now for the peak flow time of 1:15 hours, sub-catchment runoff, node total flooding, and link velocity profiles were generated. At this hour, the majority of conduits exceed the max velocity of 2m/s which is indicated by the red color. Out of 11 sub-catchments, 6 of them have max runoff exceeding 0.5 CMS and Nodes J06 have maximum node total flooding exceeding 8 Million liters as shown in Figure 13. The inundation area lies in sub-catchment B06 where sub-catchments, nodes, and conduits are indicated by red color showing maximum values. At this peak hour, flooding occurs at six nodes, and node J06 which lies in the Pulbazar area has maximum flood volume and maximum flooding rate.

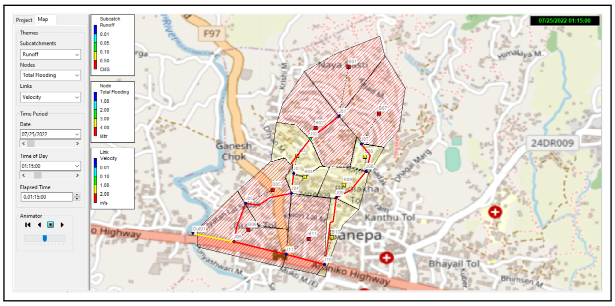

Figure 15: Map showing Subcatchment runoff, Node depth and Link velocity profile

3.3 Application of LID

After the application of permeable pavements and green roofs, there was a reduction in the runoff, peak flow, flooded nodes, and link velocity. The total runoff volume before the application of mitigating measures was 25.8 Million liters. The use of permeable pavement reduced the total runoff by 28.2% while considering the 100% green roof and 50% green roof reduced total runoff by 71.4% and 42.3% respectively. The number of nodes that were flooded was also reduced. In the original model, 6 out of 11 nos. of nodes were flooded which was reduced to 5 nos, 2 nos, and 3 nos with the use of permeable pavement, 100% green roof, and 50% green roof respectively. Likewise, the conduit velocity was also reduced with the use of these LIDs. These results are shown with the help of the graph in Figures 16, 17 & 18.

Table 2: Characteristics before and after application of LID techniques

LID Techniques	% dec in Runoff	No. of Flooded Nodes	% dec in max vel
Original Model	0	6	0
PP	28.21	4	3.11
50% GR	42.31	2	9.71
100% GR	71.41	3	6.99

For this study area, the best LID control was found to be 100% green roof followed by 50% green roof and permeable pavement. Looking at each sub-catchments, the one with the maximum impervious area was more benefited by LIDs. The green roof reduced the runoff exponentially as buildings in this area were so compacted with very fewer open spaces. B10 had the maximum impervious area as it was covered with buildings and impervious roads which has runoff reduction up to 97.19% after using LID. Similarly, sub-catchment B01 which includes a higher percentage of vegetation and hilly areas was least affected by the application of LID. The runoff reduces only by 4.5% in this sub-basin. The runoff in sub-catchment B06 including the inundation area was reduced by 28.8% using permeable pavement, 70.6% using 50% Green roof, and 94.6% using 100% Green roof.

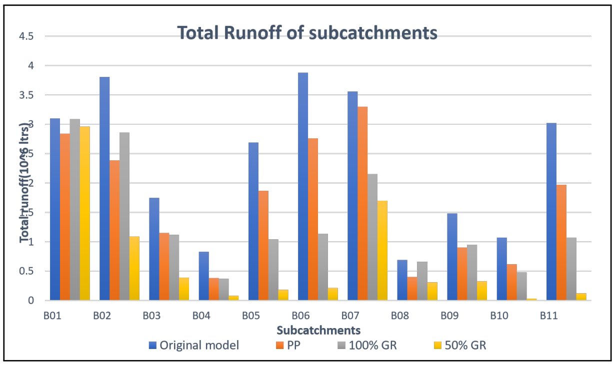

Figure 16: Total Runoff of Subcatchments

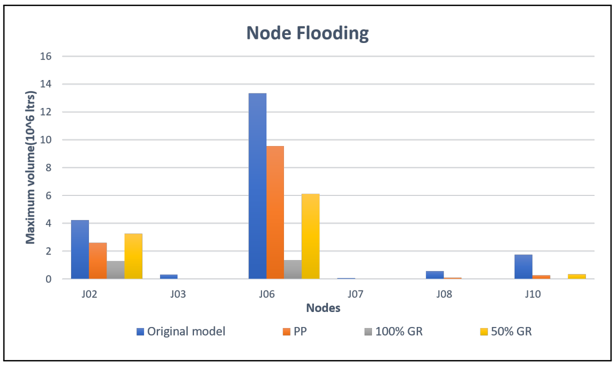

Figure 17: Max flood volume of nodes

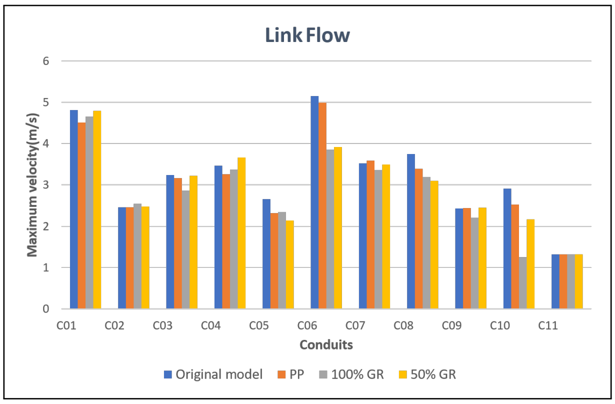

Figure 18: Flow velocity of conduits

4. Conclusion and Recommendation

The primary goal of this study was to perform an urban flood simulation and see how the practice of LID reduces flooding. The salient criteria such as peak flow, total runoff, flooded nodes are provided by SWMM output, which is important parameters for Urban drainage planning. It is felt that the parallel use of the GIS and SWMM creates a useful and time saver tool to model large catchments. It is found to be a very useful tool for determining the effect of various LID techniques in urban areas and helps in deciding the best-suited technique for the particular area.

SWMM model was used to see how sub-catchment runoff, conduit velocity, and no of the flooded node changes to the application of LID. Form this ananlysis, it can be concluded that LID practices such as permeable pavements and green roofs can operate effectively in urbanizing cities like Banepa where the core area are growing haphazardly and other LID applications like rain barrel, bioretention cells are not applicable. In this research, the application of two types of LIDs was checked independently. For further research, the effect of a combination of two or more LID controls can also be determined.

It is recommended to design the drainage and sewage lines after hydro-logical and hydraulics analysis. Adequate guidelines should be made considering extensive ground study. The government should prepare the guidelines for accessing the surface runoff for gauged and ungauged catchment separately. More rain gauge stations must be installed in this area as there might be an error in rainfall data analysis considering the rain gauge stations of the nearby area. Banepa Municipality should keep proper data records of drainage and sewerage networks. For a more accurate result, further research must be conducted to determine the exact LID modeling parameters. Furthermore, a Cost-benefit analysis could also be done to decide on various LID techniques for achieving sustainable goals. Banepa Municipality should keep proper data records of drainage and sewerage networks. It is recommended to have good research on how water used to drain off before urbanization. Project planning decisions, project design, and construction methods must take into account the level of urban flood hazard beforehand. For a more accurate result, further research must be conducted to determine the exact LID modeling parameters like Field capacity, wilting point, and conductivity slope of soil. Furthermore, a Cost-benefit analysis could also be done to decide on various LID techniques for achieving sustainable goals.

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