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Stormwater Analysis and Drainage Management in Pokhara Metropolitan City, Nepal

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Abstract

The size of the city's previously undeveloped lands is shrinking as urbanization grows. The natural and agricultural ground has been transformed with a paved surface. So one of the primary issue in urban areas has been stormwater drainage. Pokhara City has seen storm water overflow in the streets and roads during high heavy rainfall even in a short period of time due to its location in the zone of higher rainfall and quick rise in concrete constructions and paved roadways.Therefore, the purpose of this study is to estimate, using SWMM, the hydraulic capacity of the current drainage, which was built roughly two decades ago. The drainage's cross-sectional flaw is rectified in order to properly discharge runoff at the potential outfall position. Additionally, the study uses the platform offered by SWMM 5.2 software to investigate the impact of using Rain Gardens in impervious areas. According to the study's findings, the major portion of the city's drainage conduits are insufficient to convey runoff, thus they were redesigned in SWMM using a trial procedure. The modeling and analysis of the rain gardens in the various sub catchments of study area reveals a significant decrease in peak as well as total runoff.

Keywords

Storm Water, Runoff, Rain Garden, Precipitation, Drainage Network, SWMM

1. Introduction

Nepal experiences the heavy monsoons during the summer and less rainfall during the winter seasons. Most of the flooding events occur during the monsoons seasons that exists about three to four months. The drainage management of the cities are poor with respect to precipitation pattern, land use and urban planning. Therefore stormwater management is the crucial problem of the rapidly growing urban areas. Pokhara City is one of the highest rainfall receiving area of Nepal. The study found that the average annual rainfall of the past decade as 3514 mm out of which 74% of total rainfall occurred on summer (monsoon) season [1]. The major stormwater drainage network of the Pokhara city were designed and constructed in 1994 A.D with the assistance of Asian Development Bank [2]. The land use has been changed since then with the conversion of large area of city into built up and paved area. This has led to the increase in surface runoff as the infiltration of water into the ground is negligible. Pokhara receives heavy instantaneous rainfall which mostly is beyond the holding capacity of constructed drains as the drainage structures are unable to carry excess runoff and flash flood occur even in high intense short duration rainfall [3]. The streets of core part of Pokhara city like Mahendrapool, Prithvi Chowk, Srijana Chowk and Palikhe Chowk get flooded by surface runoff. Therefore the effective stormwater analysis with the sustainable drainage management is required to eradicate the problem of overflooding in the urban area.

The study area is the core part of Pokhara Metropolitan City as shown in Figure 1. The area lies from the Bindyabasini Temple (28°14'16.43"N, 83°59'0.92"E) and Nadipur (28°14'7.39"N, 83°59'20.94"E) in the North to Prithvi Chowk (28°12'28.61"N, 83°59'20.93"E) and Zero km (28°12'44.23"N, 83°58'38.35"E) in South and Seti river in East and Firke River in West with the area of 2.4 sq.km. The natural drainage of this area is Seti river in East and Firke river in West which flows along North to South direction. This area comprises of intra cities road network, major commercial centres, and residential areas. The gradient of city is in North to

South direction.

Figure 1: Red Outline Showing study Area

The objective of this study is to assess the hydraulic capacity of existing drainage networks using SWMM, and modify any insufficient drain sections so that surface runoff may be discharged without overflowing. The modelling and analyzing the influence of rain gardens in runoff using SWMM is another objective.

The history of use and construction of urban drainage system started around 5000 years ago in the Mesopotamian Empire [4].Stormwater drainage is designed to discharge runoff from urban areas as quickly as possible in order to prevent flooding. Land uses of the urban area deeply affects in the generation and management of surface runoff in the city. This runoff is a major concern in sustainable water resource management. Therefore, mitigation for the negative impacts of stormwater runoff is needed. To overcome this impact, Low Impact Development-Best Management Practices (LID-BMPs) have been developed which is used as a strategy to maintain or replicate the pre-development conditions of the catchment ecosystem, prevent pollution, or control stormwater runoff [5]. Green Infrastructure is frequently referred to as Low Impact Development (LID) in USA and Canada; Sustainable Urban Drainage Systems (SUDS) in the UK; and Water Sensitive Urban Design (WSUD) in the Middle East and Australia [6]. LID-BMPs or GI include bioretention, detention ponds, infiltration trenches, grass swales, green roofs, porous pavements, rain barrel, etc.

Rain gardens are shallow depressions in the landscape planted with local ornamental grass, perennial flowers and woody shrubs that are well adapted to wet and dry conditions and covered with a bark mulch layer or ground cover and are usually built close to cemented areas such as roads and parking lots to reduce peak runoff flow and improve water quality [7]. To manage stormwater runoff, rain gardens employ a number of techniques, including evapo - transpiration, overflow, absorption, exfiltration to local soils, underdrain discharge, absorption, particulate capture and vegetative uptake [8]. The parameters of concern for a raingarden are the percent of impervious area that are treated (% impervious treated), number of rain gardens, berm height of the rain garden, vegetation volume and conductivity through the soil medium [9]. The study in Lubigi catchment in Uganda found out that by applying 12% of rain garden GIs to each of the sub-catchments, the discharge at the outlet of the system was reduced by more than 98% [9]. Application of rain gardens in differrent proportions (1-4%) in the Xi'an city of China shows the reduction in peak flow at the outlet by 12.3-44.2% [10].

According to NJDEP (New Jersey Department of Environmental Protection), there are two general runoff computation methods that are used to compute runoff rates and volumes. One is NRCS (Natural Resources Conservation Service) methodology. The NRCS runoff equation consist of the NRCS Curve Number (CN), which is based on soil permeability, surface cover, hydrologic condition, and antecedent moisture. The curve number runoff equation is

$$Q = (P - Ia)^2/(P - Ia + S)$$

Where, Q = depth of runoff, in inches
P = depth of rainfall, in inches
Ia = initial abstraction, in inches
S = maximum potential retention, in inches

An empirical relationship between Ia and S was expressed as

$$Ia = 0.2S$$

The potential maximum soil moisture condition is based on curve number which is defined by USDA for different soil condition.It is given as:

$$S = 1000/CN - 10$$

Another method is the rational method that is used to estimate the peak rate of runoff at a specific location in a watershed as a function of the drainage area, runoff coefficient, and mean rainfall intensity for a duration equal to the time of concentration. The Rational Method is widely used throughout the world for both small rural and urban catchments [11, 12].The rational formula is:

$$Q = CIA/Z$$

Where,
Q = maximum rate of runoff (cfs or m3/sec.)
C = runoff coefficient
I = average rainfall intensity (in./hr. or mm/hr.)
A = drainage area (ac or ha)
Z = conversion factor 360 for metric

Manning's equation is used to design the drain size specially for the small areas. However, Manning's equation has been used to design the drains size of Palayam area of Calicut City in Kerala, India where the excess runoff was a threat to the environment due to dense population [13]. It is a semi-empirical equation and is the most commonly used equation for uniform steady state flow of water in open channels. Manning's equation is given as,

$$Q = \frac{1}{n} * A * R^{2/3} * S^{1/2}$$

Where, Q = water flow rate passing through the stretch of channel, (m3 /s)
A = cross-sectional area of flow perpendicular to the flow direction, (m2)
S = bottom slope of channel, (m/m)
R= hydraulic mean depth, (m)
n = Manning's constant depends on surface roughness

The values of Manning's roughness coefficient, n, for overland flow are less well understood than for channel flow because of the large variety in the terrain characteristics, the transformation between laminar and turbulent flow, the comparatively shallow flow depths, etc [14]. According to most studies as stated by [14], manning's n for a given surface cover is inversely proportional to discharge, depth and Reynolds' number.

The EPA Storm Water Management Model (SWMM) is a dynamic rainfall-runoff simulation model that is used to simulate runoff quantity and quality primarily from urban areas over the course of a single event or over a long term (continuous) event [15]. SWMM simulates all the aspects of the urban hydrologic and quality cycles including surface runoff, storage, treatment and transport through the drainage network. The overall catchment can be divided into different sub catchments in SWMM and runoff can be predicted individually from the sub catchment on the basis of indvidual properties and finally outflows can be combined using a flow routing scheme. SWMM simulates the regulation effects of LID measures on runoff, peak flow, and runoff pollution by simulating the hydrological process, including storage, infiltration, and evaporation [16].

2. Research Methodology

The research design consists of various field surveys with measurements, collection and analysis of precipitation data, extraction of land use data and characteristics, modelling in SWMM and analysis and interpretation of results. The various methodology in steps are described below.

2.1 Defining Sub Catchments and Drainage Networks

The boundaries of the study region is marked on Google Earth Pro. The different measurement tool available in Google Earth Pro is used to determine the area, length and slope of the study area. According to the slope, elevation, and drainage flow pattern, the watershed is separated into many sub catchment zones. Each sub catchmenś area is also determined using the area measurement tool. The main existing drainage as well as street network are noted and measured within the catchment area. In the field, measuring tapes are used to determine the size and shape of the cross sections of the existing drainage networks.

2.2 Collection and Analysis of Rainfall Data

The last twenty three year (2000-2022 A.D) daily rainfall data of the Airport station of Pokhara is obtained from the Meterological Department. The IDF curve for 10 year return period is prepared using the Gumbel's Extreme Value distribution [17]. The maximum twenty four hour duration rainfall in each year is sorted out from the data obtained from

Meterological department. Then the disintegration of maximum twenty four hour rainfall for different time interval for each year is carried out using the empirical formula which is given below [18].

$$P = P_{24} * (t/24)^{1/3}$$

Where P= rainfall depth in t duration (mm) P_{24}= rainfall depth in 24 hour duration (mm) t = time duration in hrs.

Mean (X_{mean}) and standard deviation (σ) of each time interval (5 min, 10 min, 15 min...24 hrs) of each individual year is calculated. Then rainfall in different time interval for 10 year return period is calculated using Gumbel's Extreme Value distribution formula given below

$$X_t = X_{mean} + \sigma K_t$$

Where K_t=frequency factor for T return period as given below

$$K_t = (Y_t - Y_n)/S_n$$

where Y_n = reduced mean in Gumbel's Extreme Value Distribution for N, S_n = reduced standard deviation in Gumbel's Extreme Value Distribution

$$Y_t = -(ln(ln(T/T-1)))$$

Where Yt = reduced variate

2.3 Preparation of Land Use Land Cover Map

Land Use Land Cover map of the study is prepared using the Arc-GIS software. The Sentinel-2 satellite images of 10 metre resolution of study area were downloaded freely. The sentinel data is preprocessed on Q-GIS software to obtain the composite image which is then further processed in Arc-Map to prepare training sample's signature class. Based on signature class of training sample, maximum likelihood classification is done to determine the different types of land use called as Forest, Buildings, Road and Barren/Agriculture areas. The land use land cover map of 2022 A.D is created to determine the pervious and impervious percentage of lands.

2.4 Modelling in SWMM

Drainage modelling is performed on EPA SWMM 5.2 which is a open source software. The interface in this software is found to be compatible and easy to use. The image of the study area obtained from the Google Earth Pro is backdropped and georeferenced in the interface area. The subcatchments, nodes, outfalls, conduits connecting different nodes and rain gauge are drawn and defined using the tools available in SWMM. Sub catchment area, slope, width, landuse characteristics, surface roughness etc. are the input parameters for subcatchments. Similarly, the invert elevation and maximum depth are input parameters for the nodes. Length, cross section sizes and surface roughness are the input parameters for the conduits. Each sub catchment is then assigned to the node and rain gauge that were defined earlier. Time series of one hour time interval rainfall data is assigned to the rain gauge. Finally simulation is performed and the model is analyzed on the basis of maximum flow, capacity and peak runoff of the sub catchments. The designing of the size and cross sections of the conduits in the network is also performed in the SWMM. The conduits with inadequate cross sections is increased on trial basis. The simulation is performed until the hydraulic capacity of conduits is within the capacity to drain the stormwater effectively. Also, the rain gardens (GI element) are assigned in each sub catchment based on the impervious area of subcatchment. The design of rain garden is done as suggested in the research findings [19, 20]. The road footpaths (patches of area between the consecutive trees grown), concreted public open places, some portions of parking lots and certain percentage of open area of residence etc. are considered for their suitability and applicability of rain gardens. The parameters of concern for a raingarden are the percent of impervious area that are treated (% impervious treated), number of rain gardens, berm height of the rain garden, vegetation volume and conductivity through the soil medium [9]. After incorporating all these parameters in SWMM, simulation and analysis is performed as mentioned above.

3. Results and Discussions

3.1 Details of Sub Catchments

The whole catchment is divided into 18 sub catchments, out of which 3 sub catchments are further divided into two tertiary sub catchments each based on the slope, elevation, drainage pattern and common flow path. The physical details of sub catchments is given in Table 1.

Table 1: Geometrical Details of Sub Catchments

S.N	Sub Catchments	Area(ha)	Width(m)	Slope %
1	SC1	8.53	224.55	2.2
2	SC2	6.56	207.55	1.8
3	SC3-I	3.54	191.61	1.8
4	SC3-II	4	155.34	1.9
5	SC4	7.59	294.02	1
6	SC5	6.8	267.72	1.6
7	SC6-I	4.98	139.91	0.8
8	SC6-II	6.22	149.58	1.2
9	SC7	14.2	355.60	1.6
10	SC8-I	6.73	220.68	1.2
11	SC8-II	10.8	307.33	0.8
12	SC9	20.1	233.73	2.1
13	SC10	13.9	200.14	0.9
14	SC11	28.3	321.42	1.9
15	SC12	14.5	225.74	1.5
16	SC13	24.3	308.74	0.9
17	SC14	13.7	181.36	1.6
18	SC15	19.3	234.53	1
19	SC16	5.27	135.07	1.1
20	SC17	13	165.21	1.8
21	SC18	1.2	47.42	1.9

3.2 Existing Drainage networks

The major drainage channel are constructed longitudinally along North-south direction with outfall at various locations. However these longitudinal drainage are connected by lateral conduits to form the integrated drainage networks. These networks were designed to carry the stormwater of the residential areas, commercial areas and streets of the city. The major drainage channel are covered with slab at top. The inlets opening to the drainage canals from the curb sides of road are insufficient with small orifice size and less in number with respect to the peak flow of runoff during the high intense rainfall which is also one of the reason for overflow of runoff in streets of Mahendrapool and Palikhe Chowk. The cross sections along with the lengths of the existing drainage canals of the different eleven streets is given in Table 2.

Table 2: Details of the Existing Drainage Canal of the Study Area

Street Number	Length (m)	Width (m)	Depth (m)	Along Roadside
1	2647	0.4-0.5	0.6	Both Side
2	2364.5	0.4-0.8	0.6-0.9	Both Side
	1260	0.4-0.8	0.6-0.9	Single Side
3	1513.7	0.5	0.6	Both Side
4	739	0.4-0.5	0.4-0.6	Both Side
5	374	0.4	0.6	Both Side
	241	0.4	0.6	Both Side
	396			Tick drain
6	529	0.4	0.4	Both Side
7	383	0.4	0.5-0.6	Both Side
	494			Tick drain
8	533	0.4-0.5	0.4-0.6	Both Side
	312.11	0.4	0.4-0.6	Single Side
9	246	0.4-0.5	0.5-0.6	Single Side
	226			Tick drain
10	653	0.4	0.5	Both Side
11	894	0.5	0.6	Both Side
	519	0.5-1	0.6-1	Single Side

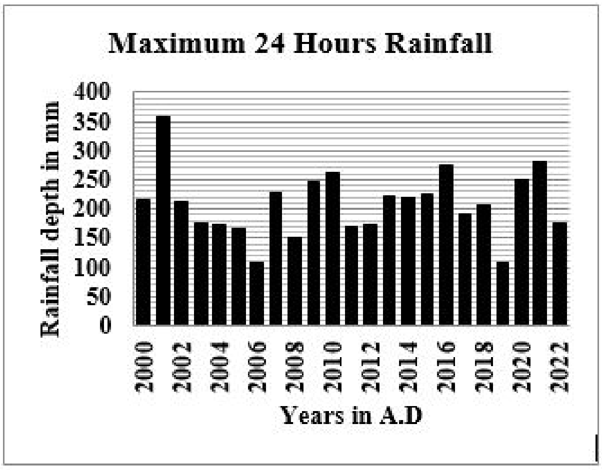


Figure 2: Maximum Twenty Four Hour Rainfall

3.3 Precipitation Data Analysis

The maximum twenty four hour duration rainfall for every year from 2002 A.D to 2022 A.D is sorted out which is shown in bar diagram shown in Figure 2. The rainfall data of one hour duration in time series is required for analysis in SWMM. Therefore the maximum twenty four hour duration rainfall is disintegrated on the different time interval and using Gumbel's Extreme Value distribution IDF curve for ten year return period is drawn out which is shown in Figure 3.

3.4 Land Use Land Cover Map

Land Use Land Cover map of the study area with its various sub catchments is prepared for year 2022 A.D. The impervious and pervious area of catchment as well as subcatchment is determined from the LULC map which is also the input parameter in SWMM. The LULC map of study area of 2022 A.D. is shown in Figure 4.

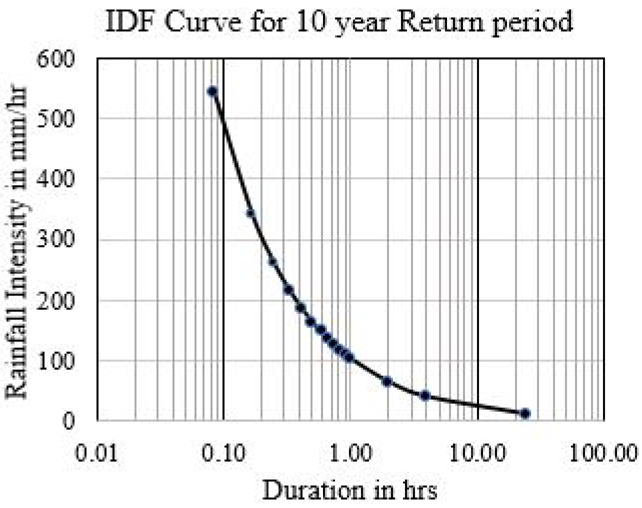
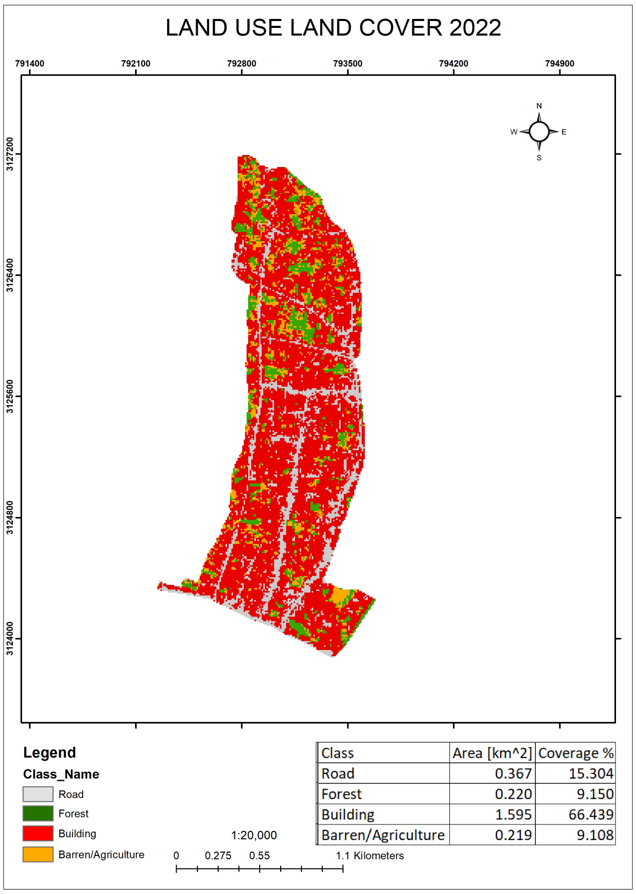


Figure 3: Intensity-Duration-Frequency curve for 10 year return period



Class	Area [km^2]	Coverage %
Road	0.367	15.304
Forest	0.220	9.150
Building	1.595	66.439
Barren/Agriculture	0.219	9.108

Figure 4: LULC Map of 2022 A.D

3.5 Status of existing drainage Networks

The drainage modelling of the study area with its backdrop image is carried out in EPA SWMM 5.2 open source software. The model consist of sub catchments, nodes, conduits, outfalls and rain gauge which are defined over it. The figure 5 shows the result of simulation showing the capacity of existing conduit over present condition. Most of the major drainage canal of the network have exceeded their capacity to carry the peak runoff. The red colour, shows that the capacity of conduit has exceeded 100%. Similarly yellow colour, green colour, sky blue colour and dark blue colour yellow indicates that the capacity is between 75-100%, 50-75%,25-50% and upto 25% respectively. This shows that the drainage conduits around Mahendrapool, Savagriha Chowk, Srijana Chowk and Prithvi Chowk need to be increased in their cross section to accommodate all the runoff.

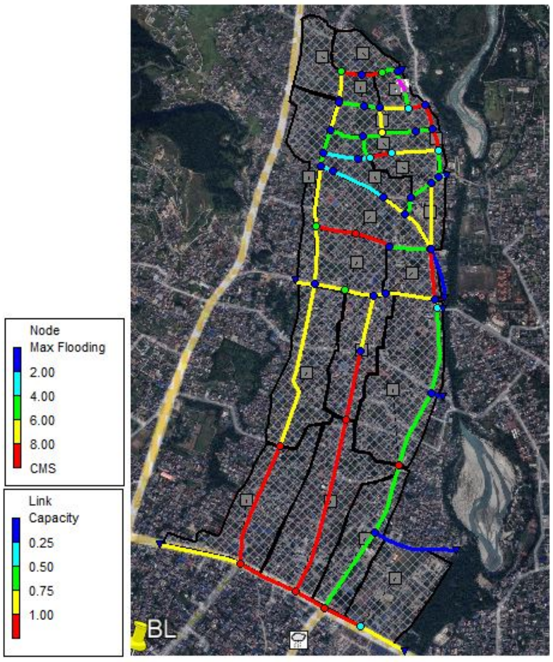


Figure 5: Conduit showing their capacity

3.6 Status after Resizing Deficit Cross Section

The cross section of various sections of conduits are increased to accommodate the runoff on trial basis in SWMM to assure the smaller cross section as much as possible. The Figure 6 shows the capacity after cross section increase. Most of the conduits are within the capacity of 75-100% in carrying the peak runoff. This shows that the drainage network are fully functional in carrying the peak runoff.

3.7 Effects of Rain Garden

Rain Garden patches of different dimension of 5mx2.5m, 5mx2m and 4mX2.5 m are assigned in

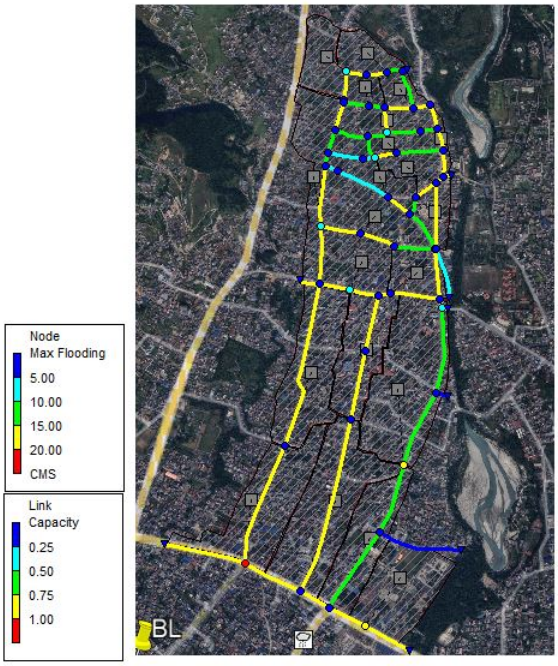


Figure 6: Conduit showing capacity after redesign

each sub catchment of the study area depending upon the impervious area and flow pattern. About 2% of impervious area of each sub catchment is converted into rain garden. The probable location of rain garden are public open concrete space , open space of residence and commercial centres and right of way of road. The soil with initial infiltration rate of 30 mm/hr, soil depth of at least 200 mm and berm height of 200 mm is taken for rain garden dessign[7]. Grasses like Napier, Stylus and Molasses; shrubs like Bougonvilla and Swamp rose; and trees like Avocado and Dhupi are favourable to grow on the rain gardens of this city. The simulation with rain garden in SWMM shows the significant reduction in runoff volume in each sub catchment which is shown in Table 3.

3.8 Comparison of Runoff

The peak runoff obtained by rational method is found to be about 1.5%-26% less than that predicted by SWMM in different sub cacthments. The higher runoff is obtained from SWMM due to the fact that rational formula uses runoff coefficient that involves geater loss [21]. The study on runoff estimation by Rational method and SWMM in Vasai, India found that the runoff from SWMM is about 28% greater than that of Rational Method [22].

Table 3: Runoff Difference with Rain Garden

Sub Catchment	Difference in Peak runoff	Difference in Total runoff
SC1	-18.32%	-6.21%
SC2	-18.31%	-6.10%
I-SC3	-20.95%	-6.08%
II-SC3	-19.27%	-5.87%
SC4	-17.70%	-6.10%
SC5	-18.92%	-6.07%
I-SC6	-16.55%	-6.26%
II-SC6	-16.36%	-6.42%
SC7	-17.47%	-6.24%
SC16	-16.74%	-6.29%
I-SC8	-17.49%	-6.25%
II-SC8	-16.24%	-6.33%
SC10	-16.73%	-6.99%
SC11	-15.64%	-6.78%
SC9	-15.49%	-6.68%
SC15	-16.22%	-6.95%
SC13	-16.25%	-7.05%
SC14	-15.62%	-6.76%
SC12	-16.17%	-6.55%
SC17	-16.10%	-6.62%
SC18	-19.05%	-6.25%

3.9 Validation

The cross section of conduit obtained from the SWMM is for the higher values of peak runoff than rational method. However using the manning's equation, cross section for few conduit is calculated for the peak rational runoff manually. For one of the conduit, the cross section from SWMM is found as 0.7mX1.1m where as through manning's equation for same conduit the cross section obtained is 0.7mX0.95m which is very close with the cross section obtained from SWMM.

4. Conclusion

The storm water analysis of the core part of Pokhara city in SWMM shows that the existing drainage network is unable to fully accommodate all the generated peak runoff for the rainfall intensity of 103.4 mm/hr of one hour duration. The capacity of more than 50% of the drainage conduits that are currently in use has been found to be exceeded. It is discovered that a 5251 meter length of drainage canal with various existing cross section sizes is too small for the runoff discharge. For all of the city's surface runoff, the new, redesigned cross sections of these drains range in size from 0.5mX0.7m to 1mX1.2m. The modeling of rain gardens in each of the study area's sub-catchments using SWMM demonstrates the significant reduction in both the peak runoff and the overall runoff from the sub-catchment. In the SWMM, the implementation of Rain Gardens merely in 2% of each sub catchment's impervious surface results in a 15-20% reduction in peak runoff and a 6-7% drop in total runoff.Therefore the concept of Green Garden is useful and requires the serious implementation measures to reduce the surface runoff for managing the stormwater drainage sustainably.

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