The Influence of Urbanization on Natural Overland Flow Paths

Amna Mohammed Al-Sayed
Planning Engineer – 2, Public Works Authority (Ashghal), Doha, Qatar
aalsayed@ashghal.gov.qa

Mohammed Amer Younus Al-Shaheen
GIS Senior Engineer, Public Works Authority (Ashghal), Doha, Qatar
moalshaheen@ashghal.gov.qa

Abstract

This paper studies the influence of urbanization on the natural overland flow paths on topography. The main objectives of this study are to: measure the effectiveness of drainage networks, study the influences of urban structure, compare the pre-and post-urban overland flow paths, and provide recommendations for flood prevention. The study was conducted on a catchment (81 km2) in Qatar that lies between Doha and Al-Rayan. Land cover, soil data, rain data, and digital elevation model (DEM) were the main inputs of the study to obtain run-off depths, time of concentration, and peak flows. The Soil Conservation Service (SCS) method was applied, where Curve Numbers (CNs) were identified for each land cover based on soil groups concerning the infiltration rate. A geographic information system (GIS) integration has provided better results. ArcMap tools have been used to study flow changes such as flow direction, flow accumulation, and stream definition. The result of the study shows that urbanization has a significant effect on the characteristics of the flow path as it causes the time of concentration to decrease, resulting in increased run-off depth and peak flow.

Keywords: Urbanization; GIS; Flood; Overland; Drainage

1 Introduction

The natural and unnatural flow of water can cause problems for infrastructure (Graham, 2010; Koval et al., 2021; Wahyudi et al., 2012). This could be due to an unnatural flood caused by rainfall in an area upstream of an area, which increases water flow in a short period of time. The same phonemena can also be caused by intense rainfall in a particular area where the systems designed to flush the water (through the storm-water collection system or through the designed or natural percolation) become overwhelmed. Thus the water is contained in an area where the soil is too dense or when there is direct precipitation on saturated areas (DPSA) (Steenhuis et al., 2005).

A high level of water absorption during rainfall or a high groundwater table can cause an area to become saturated (Ahuja, 2022; Azarnivand et al., 2020; Szabó et al., 2022). To assess such an accumulation of water in an area, many parameters, such as slope, soil structure, vegetation, flow velocity, channel density, intensity, and duration of rainfall, should be considered (Abuzied & Pradhan, 2021; Bai et al., 2022; W. Liu et al., 2021).

Different modeling techniques shall be used to understand the impact of such water clogging not only in a particular area but also in upstream and downstream areas. For such purposes, two-dimensional mapping, rainfall modeling, contour-based water passage, and volume modeling can be applied (Ornelas et al., 2017). These types of models can also be integrated in a suitably organized geographic information system (GIS) for the concerned area. The Soil Conservation Service Curve Number (SCS-CN) method is one of the best and most traditional methods for studying water overflow using GIS (Soulis, 2021). SCS mainly depends on four key factors: land cover, soil, treatment, and hydrologic conditions. In this method, the CN is identified for each land use. The CN is about the soil and is divided into four groups based on how well the soil drains. When the SCS method is used with GIS, the overflow in a catchment can be shown and analyzed in a complete way.

Urban development of many structures like buildings, roads, drainage systems, etc. has a great effect on topography and land characteristics (Zhai et al., 2021). Runoff water impacting urban areas should be discharged through a drainage system that is designed to handle the clogging volumes of overland water and is aligned to use natural terrains to flush water. Identifying the natural overland flow before urbanization should be part of urban planning, and drainage design engineers should think about using these flow paths as a basis for designing the drainage network (Zheng et al., 2018).

The study of water flow and water clogging on urbanization is important to design an efficient and effective water flushing system (T. Liu et al., 2021; Zhou et al., 2021). Due to the increased urbanization and increased population density in those areas, any water clogging or high-volume overland water flow can cause social, economic and environmental problems.

Ultimately, the analysis of the flow and the capacity of the infrastructure may consider various parameters on a spatial information system can help the planner to visualize the problem and design systems that will minimize the impact. The objective of the study is to measure the effectiveness of the drainage network in the catchment area. Then, to study the influence of the urban structure on the overland flow paths in the catchment area and compare the overland flow paths before and after urbanization. Ultimately, the study is going to provide recommendations to minimize the impact of intense rainfall in the area.

2 Methodology

An integration of SCS and GIS system is used to model water flow and water clogging in a catchment that lies between Doha and Al-Rayan (81 km^2), which is a thickly populated urban area in Qatar (Figure 1).

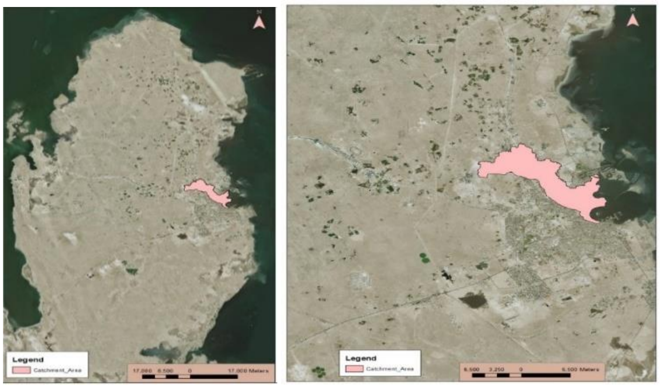
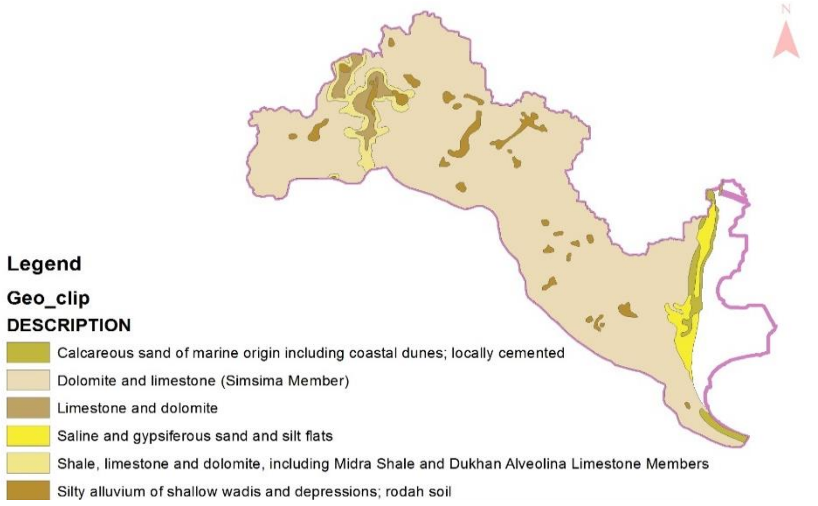


Fig. 1: Catchment Location on Qatar Map

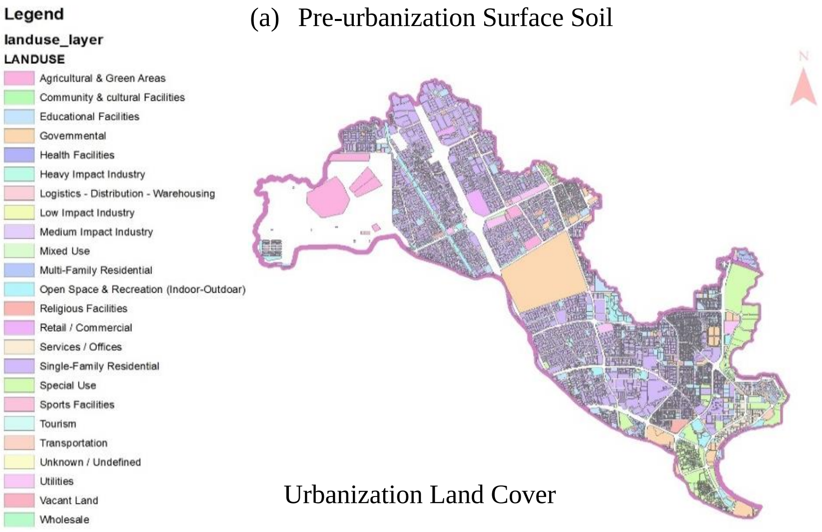
The studied area is a catchment between Doha and Al-Rayan, located in the eastern part of the country.

The area is urbanized with many residential properties though there are few parts that are non-urbanized. The study area is about 81 km^2. Doha's recent land use statistics indicate that its open spaces have reduced from 76.81% to 25.3% (Koch, 2019). There are three reasons for selecting this area are:

1. The catchment consists of different elevations where flow paths can be studied more efficiently.
2. The catchment is mainly urbanized and has non-urbanized spots where the influence of urbanization can be compared comprehensively Figure 2.
3. The capacities of the drainage systems in the urbanized area can be studied and compared with the amount of run-off water.



(a) Pre-urbanization Surface Soil



Urbanization Land Cover

Fig. 2: (a) Pre-urbanization Surface Soil Cover **(b)** Post-urbanization Land Cover

The methodology applied in this project comprised two parts: mathematical model and GIS model. Both models were integrated to obtain run-off volumes and peak flow as represented in **خطأ! لم يتم العثور على مصدر المرجع.** Page 4. SCS mathematical model was applied using soil and land use maps to identify the CN to obtain the potential maximum soil retention based on that value. Run-off value calculated using initial abstraction, total precipitation, area and soil retention. For the GIS model, DEM data were created by integrating buildings footprints and heights. A sequence of ArcMap tools were applied to obtain the time of concentration where CN was an input to longest path. Finally, to integrate both models to calculate the peak flow. The limitation of modelling accuracy with CN decreases when historical data are used.

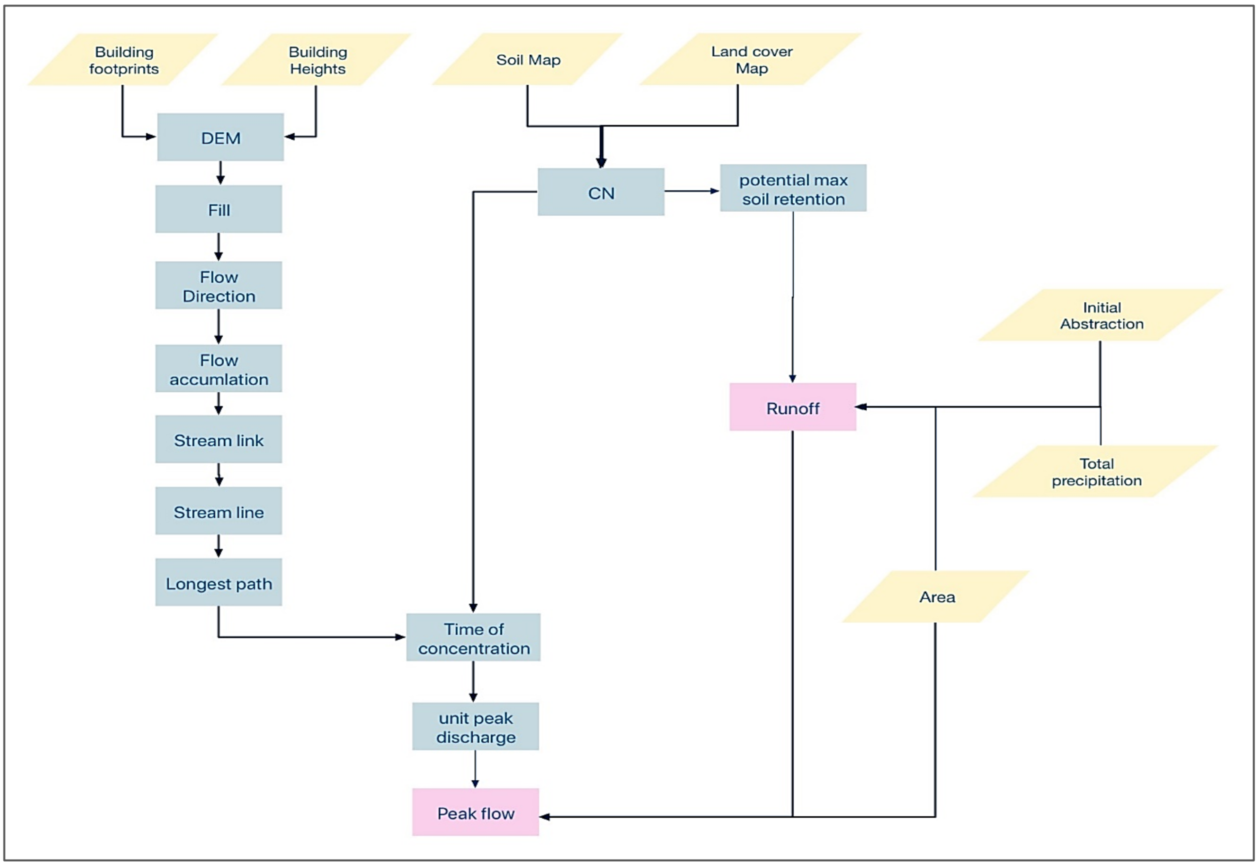


Fig. 3: Methodology Diagram

2.1 Factors

A list of factors have been identified as part of this study, summarised in **Table 1:** Summary of the Study Factors.

Table 1: Summary of the Study Factors

Factor	Description
Curve number	CN is related to soil type, infiltration, land use and water table level where soil is categorized into four soil groups based on the infiltration rates.
Land use	Classified based on usage, such as residential, commercial and open places. The cover type and condition impact the run-off volume by influencing the infiltration.
Rainfall data	The rainfall data were provided by the drainage design department in Ashghal using a 10-year rainfall event of 24 hours.
Digital elevation model	Spatially distributed hydrological attributes used to generate DEMs using LiDAR data for the whole of Qatar.
Drainage capacity	In this catchment, two pumping stations were available: • SW 3, which actually drains most of the catchment and has a capacity of 6.3 m3/s. • SW 4, which actually drains a small part of coastal area; pearl etc. and has a capacity of 0.8 m3/s. This gives a total pumping station capacity of 7.1 m3/s.

2.2 SCS-CN Method

SCS-CN method was implemented to predict direct run-off volumes in the studied area for a 10-year rainfall event depending on four important factors, among which soil type and land cover were important. The following three equations were used to calculate run-off volume generated, as attained from Ashghal's Drainage Design Manual (chapter 4)(PWA, 2006).

$$Q = \frac{(P-I_a)^2}{P-I_a+S} \tag{1}$$

$$S = \frac{1000}{CN} - 10 \tag{2}$$

$$CN_w = \frac{\sum_1^n CN_i A_i}{\sum_1^n A_i} \tag{3}$$

Where,

Q = Run-off generated (in).

P = Total precipitation (in).

S = Potential maximum soil moisture retention after run-off begins (in).

I_a = Initial abstraction (in) or infiltration or rainfall interception from Table A.2 -Appendix (A).

CN_i = The CN for particular land from Table A.1- Appendix (A).

A_i = Area of each land use.

2.3 Determine Peak Flow

Peak flow is the rate of the maximum discharge of run-off in a storm event. Peak flow depends on time of concentration and unit peak discharge. To calculate the peach flow, the equations below were obtained from the Urban Hydrology for Small Watersheds Manual published by the United States Department of Agriculture (Technical Relase55).

$$t_c = 0.0136 \times L^{0.8} \times (\frac{1000}{CN} - 9)^{0.7} H^{-0.5} \tag{4}$$

$$H = \frac{\text{highest elevation} - \text{lowest elevation}}{L} \tag{5}$$

$$q_u = 10^{[C_0 + (C_1)(log t_c) + (C_2)(log t_c)^2]} \tag{6}$$

$$\text{Peak flow} = q_u * A * Q \tag{7}$$

Where,

t_C = Time of concentration in (hr)

CN = Hydrologic area-weighted CN

A = Area of catchment (km^2)

Q = Run-off (in)

L = Hydraulic watershed length (m)

H = Average watershed land slope (m/m)

q_u = Unit peak discharge (csm/in)

C0, C_1, C_2 = Dimensionless coefficient for rain type II listed in Table A.4 - Appendix (A).

2.4 SCS Implementation

The results show that an urban area has a higher run-off depth than a rural area because Q is bigger, as shown in Table 2 page 6. This difference results from the changes in the characteristics of the topography due to urbanization, where the infiltration rates and precipitation decreases and land cover change and results in higher run-off depth.

Table 2: SCS Calculation of Q

	Post-urbanization	**Pre-urbanization**
CN weighted	92	67
Ia	0.174	0.41
P	1.984	1.984
Ia/P	0.088	0.207
S	0.915	4.927
Q	**1.202**	**0.381**

2.5 GIS Implementation

The The following steps are applied by sequencing the use of GIS tools to generate the flow stream in ArcMap and then calculating the peak flow using the stream create:

- Generate DEM of the Catchment Area.
- Fill Tool Applied to the Catchment Area.
- Flow Directions defined of the Catchment Area.
- Flow Accumulation of the Catchment defined.
- Stream Link Applied to the Catchment Area.
- Stream Lines Identified in the Catchment Area.
- Longest Path Identified in the Catchment Area.

2.6 Peak Flow and Drainage Capacity

Two scenarios are discussed for the post-urbanization. First, all run-off water (including water accumulated on buildings, etc.) is considered and flash to the drainage. Second, only water from the Right of Way is considered and flash to the drainage. The time of concentration, qu, peak flow and all related parameters are calculated and represented in Table 3.

Table 3: Peak Flow Calculations

Parameters	**Post-urbanization**	**Post-urbanization (RoW)**	**Pre-urbanization**
CN weighted	92	92	67
L (m)	22,620	22,620	30500
Lowest elevation (m)	1.2	1.2	2
highest elevation (m)	23	23	31
H (m/m)	0.00096	0.00096	0.00095
Tc (hr)	34.5	34.5	98.8
I_a (in)	1.174	0.174	0.410
P (in)	1.98	1.98	1.98
I_a/P	0.6	0.1	0.2
C_0	2.55	2.55	2.509
C_1	–0.615	–0.615	-0.619
C_2	–0.164	–0.164	-0.141
q_u ($m^3/s/in/km^2$)	0.18	0.18	5.2
A (km^2)	81	29	0.06
Q (in)	1.20	1.20	0.38
Peak Flow (m^3/s)	**17.6**	**6.3**	**1.8**

It is observed that the post-urbanization time of concentration (tc) for both scenarios is less than the post-urbanization time, which means that more water will accumulate in less time, causing the run-off depth (Q) to increase. The peak flow of the post urbanized catchment has the highest value in comparison with the other values with a significant difference.

Because the capacity of pumping stations is 7.1 m3/s, the capacity of the pumping station will be able to discharge the total amount of ROW run-off for a 10-year rainfall event intensity. If run-off water falls into the stream from other sources (e.g. building roofs), the drainage capacity will not be able to discharge these amounts, thereby resulting in the flooding of the urban area and harm to the residents.

3 Results and Findings

3.1 Influence of Urbanization on Flow Paths

The results show that overrun characteristics vary due to changes in land use, geology, topography and more. It can be observed that urban development of the catchment has a notable effect on the hydrological response based on the amount of change by human activities. As the land is covered by roads, buildings, etc., it will have a smaller capacity to store water, causing flood risk mainly in areas with dense population. Due to storage capacity, urban flow rises quickly with higher peak discharge rates of 17.6 m3/s, whereas it is only 3 m3/s for rural area.

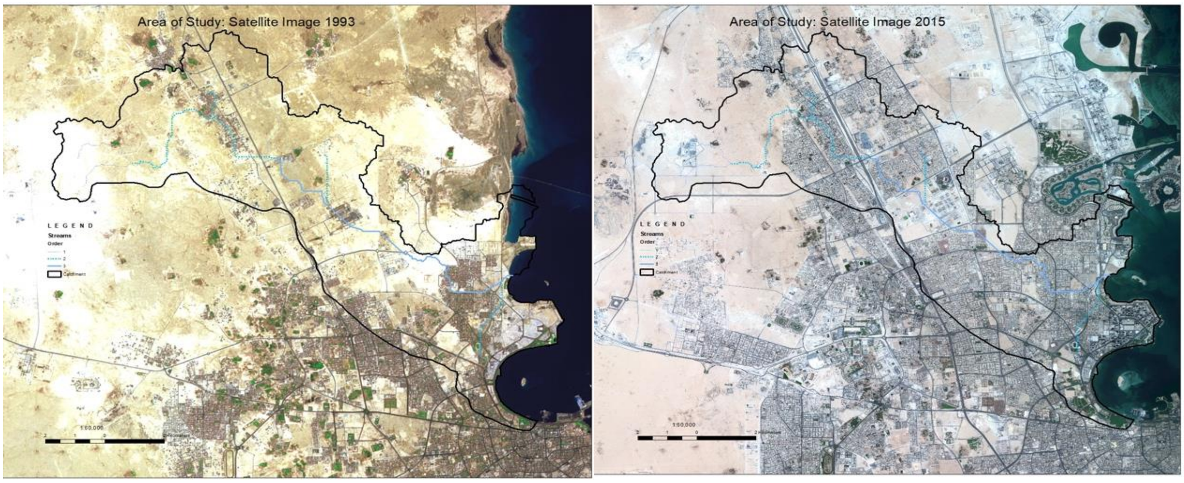


Fig. 4: Satellite Images for Years 1993 and 2015

This shows a significant raising of peak flows due to human activities where water is blocked by structures and forced to change the flow, causing accumulation of water in urban areas. Figure 4 shows the urban development difference in the catchment area pre- and post-urbanization. Moreover, urbanization causes reduction in evapotranspiration and percolation of water. This results in the acceleration in run-off and accumulation of water in various areas. In addition, there is the material covering the soils, which reduce the amount of water that may be infiltrated by soil and increase the run-off rate.

3.2 Analyse Drainage Design Capacity

Urbanization causes a loss of natural flood storage that should be replaced by artificial drainage networks. When the drainage capacity is inadequate, run-off occurs in urban areas. The results show the drainage network in the catchment will be able to discharge the amount of rain considering only ROW run-off. Due to the improper commitment to the standards considered whilst designing the drainage network, for this catchment, most of water from building rooftops and other sources also run into the ROW, causing high flood level.

The amount of water falling into the stream from sources other than ROW has been studied based on the land cover map. Different area percentage of these sources are added gradually to show how much the drainage network can actually discharge before causing a flood in the area. Table 4 shows the peak flows for different percentages.

Table 4: Flow Peaks of Adding Different Area Percentages

Percentage (%)	**Area other than ROW% (km^2)**	**Total area (km^2) [ROW + non-ROW%]**	**Peak flow (m^3/s)**	**Peak flow difference**
10%	5	34	7.36	4%
20%	10	39	8.47	19%
30%	16	44	9.59	35%
40%	21	50	10.71	51%
50%	26	55	11.82	67%
60%	31	60	12.94	82%
70%	36	65	14.05	98%
80%	41	70	15.17	114%
90%	47	75	16.29	129%
100%	52	81	17.40	145%

These results show the drainage can handle the water accumulated in the stream only for 8% of other areas. If that percentage increases, it will result in increasing the amount of peak flow to cause flooding of the catchment. This is because the excess amount of water is not considered in the design of the drainage network. For this catchment, the area was urbanized where the drainage network was constructed between 2000 and 2014, whilst few ones were newly constructed between 2016 to 2018. This may impact the condition of the drainage network, where it will not be able to flash the run-off water volumes. Moreover, part of the drainage network in that catchment is negative and part is positive. Negative networks are constructed but not connected to the main network, whilst positive networks are connected.

These negative networks are flushed in soakaways or sub-tanks where water will evaporate. This means that some portion of the run-off water will not be discharged through the pump station where it will be discharged in the ground, resulting in an increased water table level if the soakaway cannot handle the amount of water causing the soil to be saturated anot able to absorb the water. Compared with the flood history in the catchment for the year 2017, the catchment had slight floorings for the past years, which can be considered proof for the results obtained from this study, as shown in Figure 5.

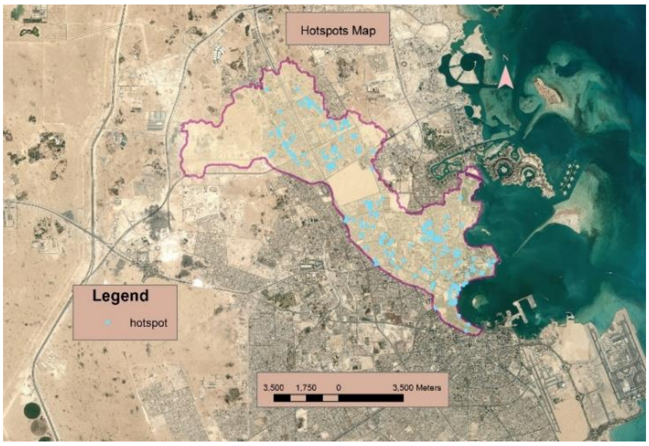


Fig. 5: Flooding History of the Catchment

3.3 Compare Flow Paths

It is observed the pre-urbanized stream had one continuous flow with many branches, whilst the post-urbanization split into two streams with less branches, thus causing the stream length to be shorter. Furthermore, the longest path of the pre-urbanized stream is around 31 km, whilst the longest path of the post-urbanized stream is only 22 km. This is due to the build-up of roads and other structures that lead the water to flow in a certain and defined path instead of running naturally along the topography Figure 6.

The amount water in urban areas is accumulated in a stream with a shorter length for the post-urbanized than the pre-urbanized, which is much longer and causes the water accumulation depth to increase from 0.3 in to 1.3 in for the post urban. On the other hand, the time of concentration for the post-urbanization is reduced due to the reduction in the flow length, which can be observed from the calculation results in Table 3 Page 6 as both have a directly proportional relationship.

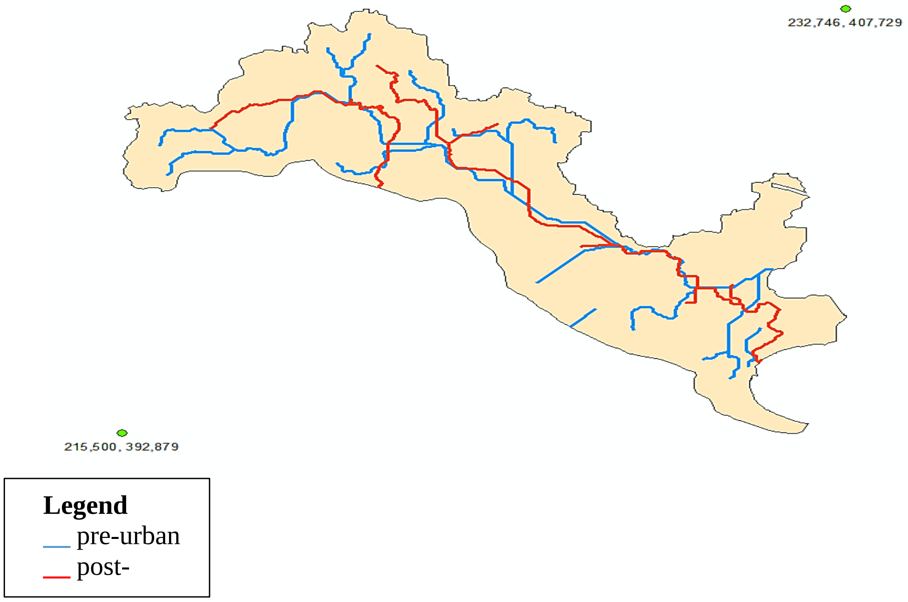


Fig. 6: Comparison of Pre- and Post-urbanized Streams

4 Conclusion and Recomendations

In this study, the influence of urban structure on natural flow paths of water is presented. Due to the increase of population density and urbanization, high volumes of water flow accumulated and caused floods. The project was conducted for an 81 km2 catchment that lies between Doha and Al-Rayan in Qatar. The analysis measured the catchment's drainage capacity for a 10-year rainfall event of 24 hours where all run-off water was assumed to be discharged through the pump station.

Parameters such as soil data, land cover, and rain fall data are considered in this project. As more factors were considered, the efficiency of the model improved and became more accurate. The SCS method was applied for this study, where soil type was the main factor to identify the CN for each land use. GIS was integrated to represent flow directions and accumulations and to identify stream flow where DEM was used as an input to asses pre- and post-urbanization flow.

The results of the study showed that urbanization increased the run-off volume in the catchment and the peak flow by reducing the time of concentration. The characteristics of the flow paths has been changed due to human activities in the catchment, causing the flow path length to decrease. The techniques applied in this project were useful where changes in flow paths pre- and post-urbanization were expressed in an efficient way.

Studying flow paths requires knowledge of several areas—GIS, geology and hydrology—to conduct a more accurate study. Understanding the natural flow of water is an important aspect for planners, and designers need to consider it to have a proper drainage design and to prevent flooding. From this study, it is recommended that the following actions be considered to prevent flooding:

1. Drainage systems should be expanded to increase their capacity for high stream flows in order to prevent flooding in case the amount of water if runoff increased to be more than 8% from other areas in addition to the ROW.
2. the status of existing drainage should be studied and periodicaly monitored to prevent any network blocking. This will make the drainage network more efficient and capable of discharging the amount of water that it is designed for.
3. Accumulated water in areas rather than ROW should be drained in places other than the road as it impacts the other land features.
4. Infiltration should be considered for water storage in the soil, such as in infiltration trenches, sokaways and permeable pavements.
5. In order to reduce the amount of runoff water and increase the value of CN, planting more vegetation in streets, schools and hospitals and encouraging people to plant in their backyards can help decrease run-off as green areas and vegetation increase the possibility of water aborbtion.

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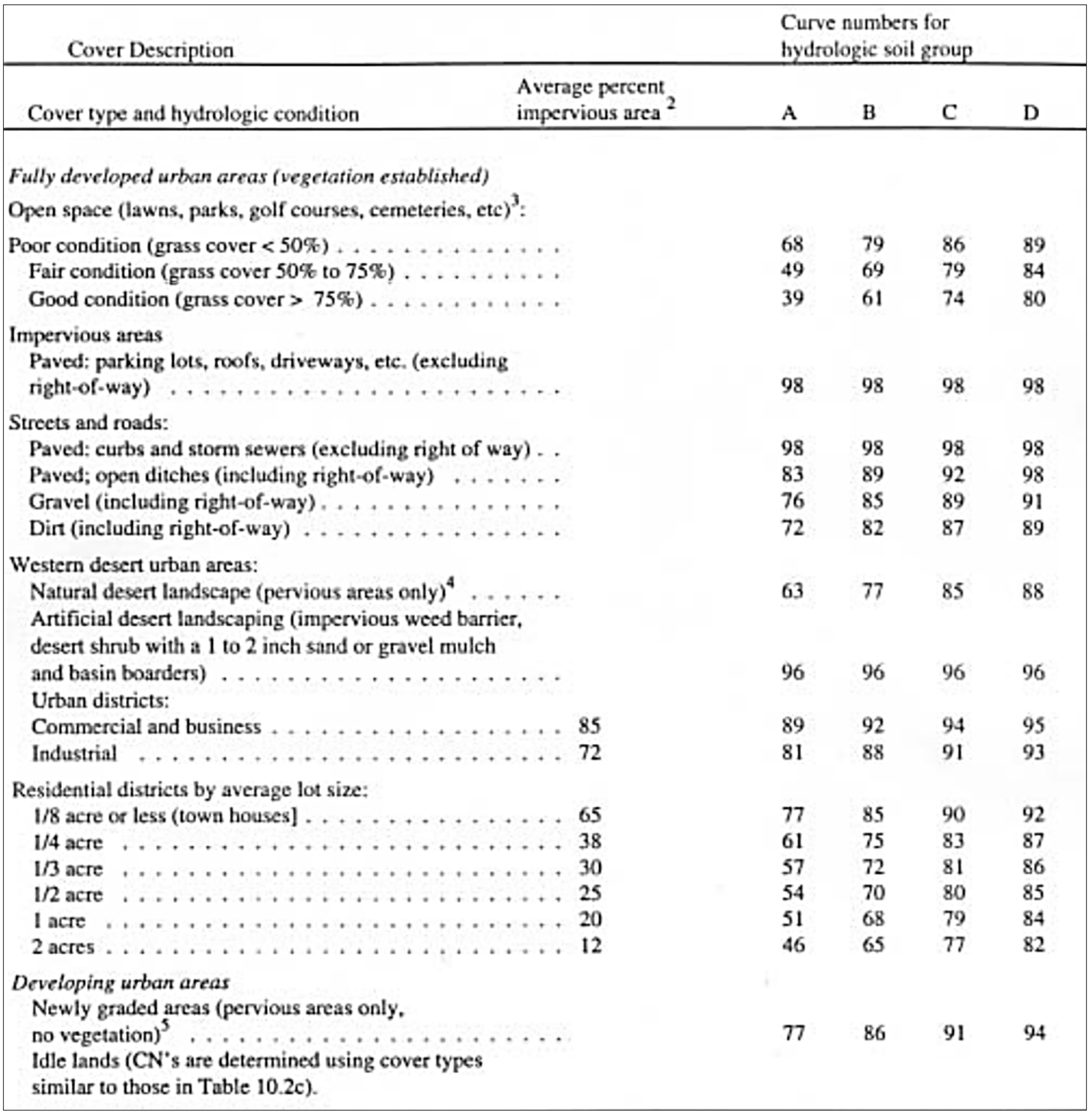
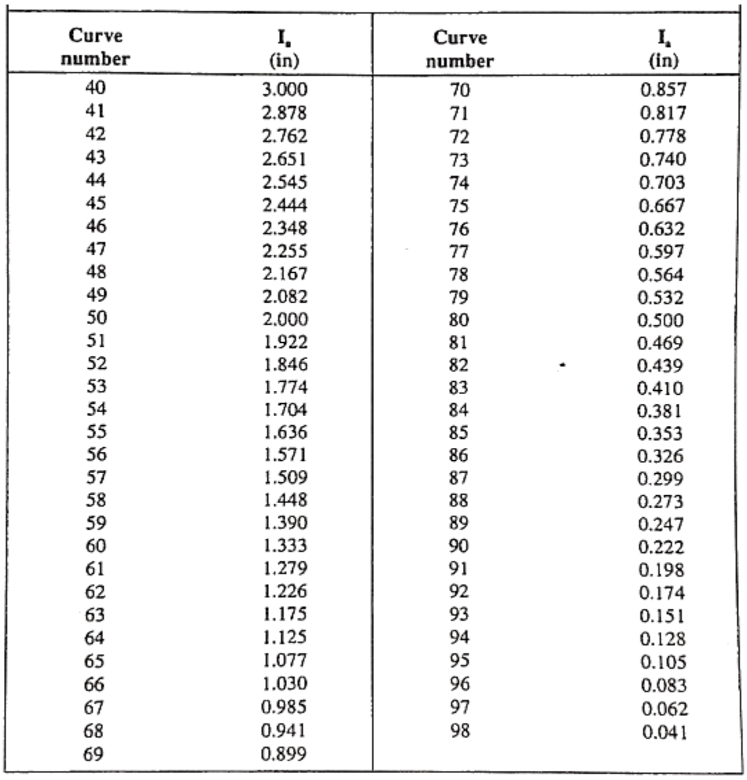
Appendix A: Construction Contract Administration Framework

Table A.1: Runoff Curve Number for Urban Areas



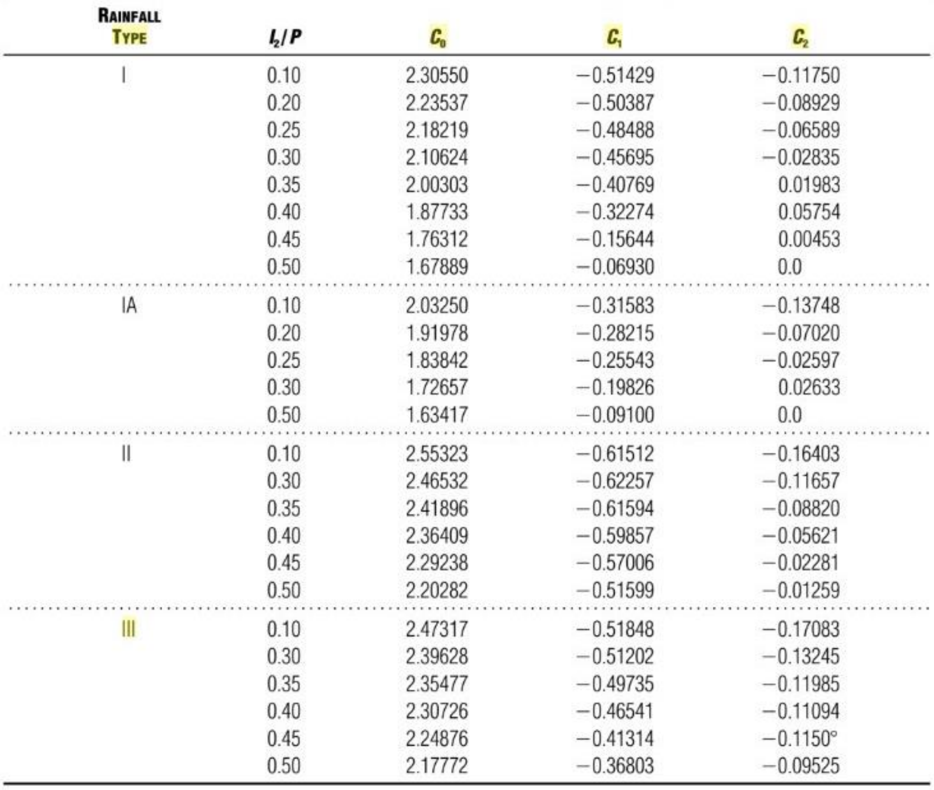
Cover Description		Curve numbers for hydrologic soil group			
Cover type and hydrologic condition	Average percent impervious area [2]	A	B	C	D
Fully developed urban areas (vegetation established)					
Open space (lawns, parks, golf courses, cemeteries, etc)[3]:					
Poor condition (grass cover < 50%)		68	79	86	89
Fair condition (grass cover 50% to 75%)		49	69	79	84
Good condition (grass cover > 75%)		39	61	74	80
Impervious areas					
Paved: parking lots, roofs, driveways, etc. (excluding right-of-way)		98	98	98	98
Streets and roads:					
Paved: curbs and storm sewers (excluding right of way)		98	98	98	98
Paved; open ditches (including right-of-way)		83	89	92	98
Gravel (including right-of-way)		76	85	89	91
Dirt (including right-of-way)		72	82	87	89
Western desert urban areas:					
Natural desert landscape (pervious areas only)[4]		63	77	85	88
Artificial desert landscaping (impervious weed barrier, desert shrub with a 1 to 2 inch sand or gravel mulch and basin boarders)		96	96	96	96
Urban districts:					
Commercial and business	85	89	92	94	95
Industrial	72	81	88	91	93
Residential districts by average lot size:					
1/8 acre or less (town houses]	65	77	85	90	92
1/4 acre	38	61	75	83	87
1/3 acre	30	57	72	81	86
1/2 acre	25	54	70	80	85
1 acre	20	51	68	79	84
2 acres	12	46	65	77	82
Developing urban areas					
Newly graded areas (pervious areas only, no vegetation)[5]		77	86	91	94
Idle lands (CN's are determined using cover types similar to those in Table 10.2c).					

Table A.2: Ia value for runoff CN



Curve number	I_a (in)	Curve number	I_a (in)
40	3.000	70	0.857
41	2.878	71	0.817
42	2.762	72	0.778
43	2.651	73	0.740
44	2.545	74	0.703
45	2.444	75	0.667
46	2.348	76	0.632
47	2.255	77	0.597
48	2.167	78	0.564
49	2.082	79	0.532
50	2.000	80	0.500
51	1.922	81	0.469
52	1.846	82	0.439
53	1.774	83	0.410
54	1.704	84	0.381
55	1.636	85	0.353
56	1.571	86	0.326
57	1.509	87	0.299
58	1.448	88	0.273
59	1.390	89	0.247
60	1.333	90	0.222
61	1.279	91	0.198
62	1.226	92	0.174
63	1.175	93	0.151
64	1.125	94	0.128
65	1.077	95	0.105
66	1.030	96	0.083
67	0.985	97	0.062
68	0.941	98	0.041
69	0.899		

Table A.3: Coefficients for SCS discharge method



RAINFALL TYPE	I_a/P	C_0	C_1	C_2
I	0.10	2.30550	−0.51429	−0.11750
	0.20	2.23537	−0.50387	−0.08929
	0.25	2.18219	−0.48488	−0.06589
	0.30	2.10624	−0.45695	−0.02835
	0.35	2.00303	−0.40769	0.01983
	0.40	1.87733	−0.32274	0.05754
	0.45	1.76312	−0.15644	0.00453
	0.50	1.67889	−0.06930	0.0
IA	0.10	2.03250	−0.31583	−0.13748
	0.20	1.91978	−0.28215	−0.07020
	0.25	1.83842	−0.25543	−0.02597
	0.30	1.72657	−0.19826	0.02633
	0.50	1.63417	−0.09100	0.0
II	0.10	2.55323	−0.61512	−0.16403
	0.30	2.46532	−0.62257	−0.11657
	0.35	2.41896	−0.61594	−0.08820
	0.40	2.36409	−0.59857	−0.05621
	0.45	2.29238	−0.57006	−0.02281
	0.50	2.20282	−0.51599	−0.01259
III	0.10	2.47317	−0.51848	−0.17083
	0.30	2.39628	−0.51202	−0.13245
	0.35	2.35477	−0.49735	−0.11985
	0.40	2.30726	−0.46541	−0.11094
	0.45	2.24876	−0.41314	−0.1150°
	0.50	2.17772	−0.36803	−0.09525

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