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Application of Rational Formula to Estimate Peak Flood for a Partially Urbanized Catchment

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ABSTRACT

The urbanized catchment is a complex hydrological system owing to the close interaction between natural and human activities, influenced by spatial and temporal variability. Urbanized catchments are mostly affected by floods caused by cloudbursts, resulting in generated peak discharge. Therefore, analyzing peak discharge is an important concern. The Rational Formula (RF) stands out as a widely utilized equation in applied hydrology for calculating peak discharge. Its prevalence is attributed to its simplicity and adept balance between theoretical principles and the accessibility of data in practical applications. The current studies address the application of RF on an ungauged partially urbanized catchment. Certain parameters e.g. catchment area, drainage network, soil information, land use land cover was extracted through application of GIS tools. The intensity–duration–frequency rainfall curves and time of concentration T_c were estimated for the study area. Finally, the Gumbel distribution was applied for the intensity duration frequency analysis. The intensities varied from 86.55mm/hr to 98.79mm/hr for a station for 25-years & 50-years return periods which produces the peak floods of 291.24m^3/s & 332.41m^3/s respectively.

KEYWORDS: Rational Formula, Peak Discharge, Urbanized Catchment

1 INTRODUCTION

The hydraulic dynamics of watersheds undergo substantial changes due to urban development, primarily driven by modifications in land cover and land use, particularly the expansion of impervious surfaces. These changes result in shifts in various hydrological parameters within watersheds, including alterations in inundation depth, runoff volume, and the peak discharge of runoff. This is primarily attributed to impervious areas, which emerge as principal contributors to surface runoff in urban environments[1, 2].The assessment of precipitation runoff in urban environments presents a significant scientific challenge with crucial implications for urban planning. This process holds paramount importance for city planners due to its direct and indirect impacts on the daily lives of numerous residents[3].Excessive precipitation and elevated runoff exert deleterious effects on both vehicular movement and the resilience of urban infrastructure. The precise measurement of storm runoff holds significant importance in evaluating various

environmental phenomena, including the transport of sediment and pollutants, as well as the erosion or deposition of sediment within a watershed [4-7]. Watersheds represent the favored hydrological entity for the estimation of runoff due to constraints in urban hydraulics posed by storm water inlets. Prior research has demonstrated that the spatial manipulation of topographic data with high resolution is a potent technique for delineating watersheds[8-10]. Estimating runoff in expansive urban watersheds poses a scientific challenge owing to the intricate interplay of factors influencing surface runoff. These factors encompass elevation, land cover, and land use, introducing dynamic complexities to the runoff estimation process[11, 12]. The rational method constitutes a straightforward and broadly embraced empirical model utilized for the estimation of runoff[13]. The rational method was initially devised to aid in the planning of sewer and drainage infrastructures by furnishing an approximate assessment of the peak runoff discharge[13, 14].
In 2021, Islamabad, the capital of Pakistan, experienced an extreme cloudburst-induced flood in sector E-11. This event led to the generation of a peak flow within the sector, significantly impacting the entire region of E-11, Islamabad. Consequently, the current research aims to analyze the peak discharge using the rational formula to predict potential future cloudburst conditions in E-11, Islamabad.

2 STUDY AREA & DATA COLLECTION

Islamabad, the capital city of Pakistan was planned and built in the 1960s. The geographic area of the capital is 906 km^2 and average elevation of the area varies from 500 to 700 m above mean sea level. E-11 Sector lies on the northern outskirts of Islamabad City, near the Margalla Hills National Park. The selected study area lies in E-11 sector as shown in Figure 1.

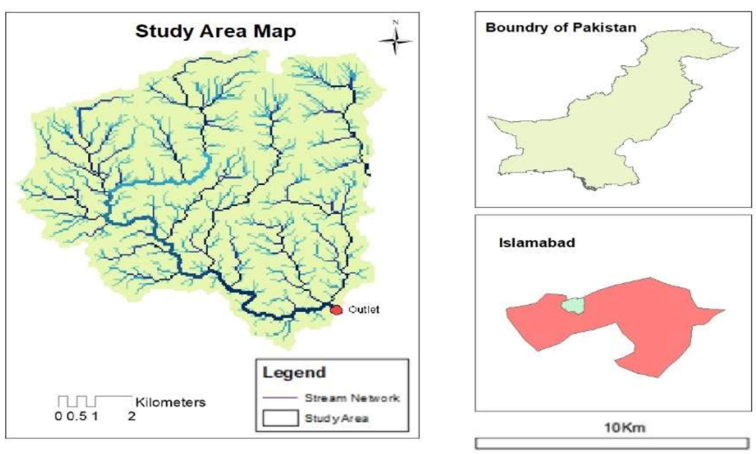

Figure 1: Location Map of the Study Area

The digital elevation model (DEM) of 30 meters resolution was downloaded from https://srtm.csi.cgiar.org/srtmdata/. The DEM was used to delineate the watershed boundaries and generate the stream network. Land use land cover (LULC) maps were extracted from satellite imagery (30-m) obtained from USGS Earth Explorer (https://earthexplorer.usgs.gov/) which comprised of Landsat Operational Land Imager (OLI) 8-9 OLI/TIRS C2 L2 for year 2021. Similarly, the soil classification map was obtained from the FAO Digital Soil Map of the World (DSMW) (https://www.fao.org/) soil database. The rainfall data was gathered from Pakistan Metrological Department (PMD), Islamabad.

3 METHODLOGY

3.1 Terrain Preprocessing

The delineation of the catchment was performed using terrain preprocessing tools within the ArcGIS program. The output data generated from terrain preprocessing were then employed in HEC-GeoHMS, for project setup (Figure 2). Subsequently, from the results obtained through HEC-GeoHMS, physical characteristics such as catchment area, slope, and length of the flow path were extracted. This extracted data was utilized in the calculation of peak discharge using the rational method for different return periods, and the outcomes are detailed in Table 1.

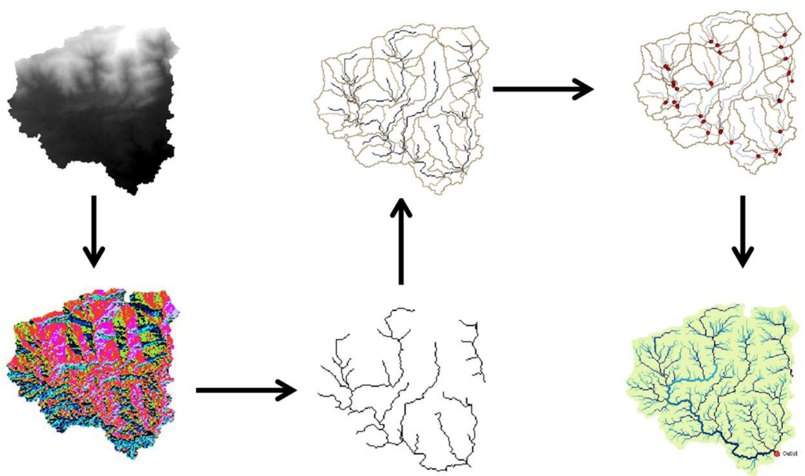

Figure 2: Terrain Preprocessing results using HEC-GeoHMS

Table 1: Physical characteristics of the study area

Catchment Area (Km^2)	Length of flow path (m)	Catchment slope (m/m)
19.266	12480.00	0.20307

3.2 Land Use-Land Cover (LULC) & Soil Classification

Unsupervised classification methodology was employed to discern alterations in LULC within the watershed. The watershed underwent categorization into three primary classes: Pastureland, Built-up Area, and Forest Land. Utilizing ArcGIS, maps depicting the resultant land cover and land use, as well as overlay maps, were generated. The specific distribution of land use within the study area is illustrated in Figure 3, while Table 2 provides a quantitative representation of the spatial extent occupied by each respective land use class.

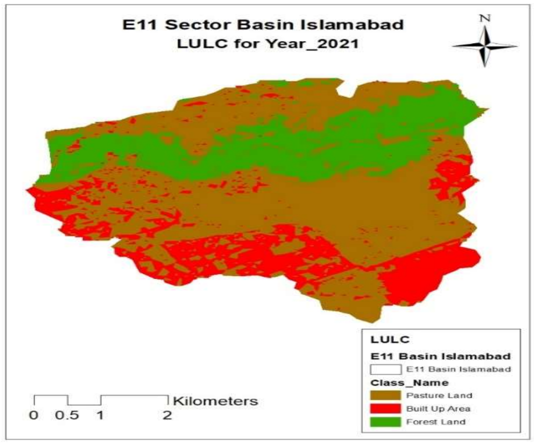

Figure 3: Study area's classified land use map

Table 2: Land use Land cover classifications for the study area

Class Name	**Area (Km^2)**	**Percent Area (%)**
Pastureland	8.97	46.54
Built-up Area	5.54	28.75
Forest Land	4.76	24.70

The soil classification map was derived from the FAO Digital Soil Map of the World (DSMW) soil database (https://www.fao.org/). The HSG D (clay loam, silty clay loam, sandy clay, silty clay, clay) dominated the research region, accounting for 100% of the overall study area. Figure 3 depicts the soil map for the research region.

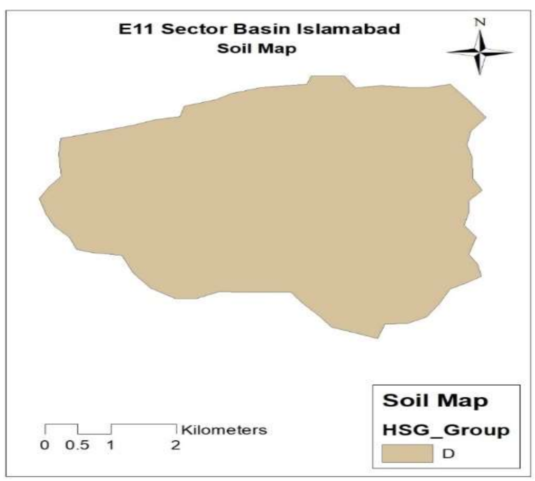

Figure 4: Soil map for study area

3.3 Rational Method

The rational formula has proven to be successful in estimating maximum water flows in smaller watershed areas, typically ranging up to 50 square kilometers in size. A detailed discussion of the rational technique and the practice followed in different countries is given in [17]. This is the rational method's basic equation. The following equation is written for field application:

$$Qp = \frac{1}{3.6} CIA \quad (1)$$

In this equation, Q_P represents the peak flow rate in cubic meters per second, C is the runoff coefficient, I stand for rainfall intensity in millimeters per hour during the Tc period with an exceedance probability (P), and A denotes the drainage area in square kilometers. These variables play a crucial role in present hydrological investigation.

3.3.1 Time of Concentration (Tc)

The Kirpich Equation from 1940 is a commonly employed formula that establishes a connection between the time of concentration (Tc) and the catchment's length of travel and slope, as depicted below.

$$T_C = 0.01947(L^{0.77} \times S^{-0.385}) \quad (2)$$

In this context: Tc represents the time of concentration in minutes, L stands for the maximum length of water travel in meters, and S denotes the slope of the catchment in percentage.

3.3.2 Rainfall Intensity (I)

The rainfall-frequency-duration relationship for the specified catchment area provides the rainfall intensity aligning with a duration Tc and the desired probability of surpassing P (equivalently, the return period T = 1/P).

$$I = (\text{Max rainfall depth for } T_c\text{-min duration}/T_c) \times 60 \quad (3)$$

3.3.3 Runoff Coefficient (C)

Occasionally, the sub-areas of a non-uniform catchment divide in a complex manner, making it challenging to distinguish discrete subzones. In such situations, a weighted equivalent runoff coefficient, denoted as Ce, is used as a substitute for C, as illustrated below.

$$C_e = \frac{\sum_1^N C_i A_i}{A} \quad (4)$$

4 RESULTS & DISCUSSION

4.1. IDF Curves

The Pakistan Meteorological Department (PMD) provided daily 24-hour rainfall statistics from 2007 to 2022. The data was evaluated, and the yearly maximum 24-hour rainfall data was obtained, as shown in Figure 5.

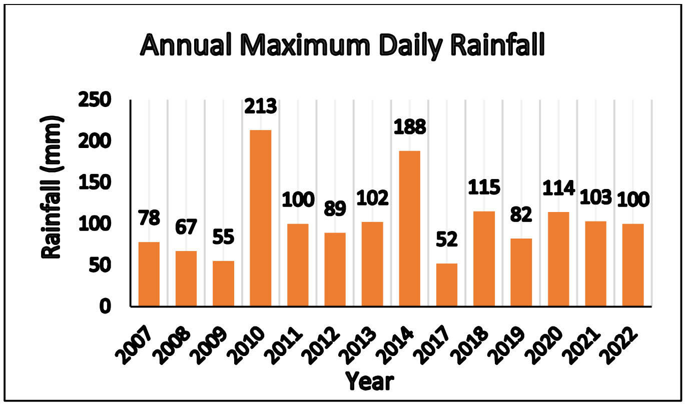

Figure 5: Annual Maximum Daily Rainfall

A shorter length rainfall series created from daily rainfall data using the IMD formula mentioned below[16].

$$Pt = p_{24}\left(\frac{t}{24}\right)^{\wedge\frac{1}{3}} \quad \textbf{(5)}$$

In this context, Pt represents the rainfall in millimeters for a duration of t hours, P24 denotes the daily rainfall data in millimeters, and t stands for the shorter duration in hours. Gumbel's Extreme Value distribution method is applied in this study to establish the probability distribution for each selected duration data series, as outlined in Table 3.

Table 3: Quantifies rainfall intensity in mm/hr throughout various durations and return periods for the watershed, using Gumbel's Extreme Value Distribution for computations.

Duration (hr.)	Mean	S.D.	25 Yrs.	50 Yrs.
0.08	15.77	6.91	412.50	470.81
0.17	19.87	8.70	259.86	296.59
0.25	22.74	9.96	198.31	226.34
0.5	28.66	12.55	124.93	142.59
1	36.10	15.82	78.70	89.82
2	45.49	19.93	49.58	56.59
12	82.66	36.21	15.01	17.14
24	104.14	45.62	9.46	10.80

The intensity duration frequency (IDF) curves for the return periods of 25 and 50 years are shown in Figure 6.

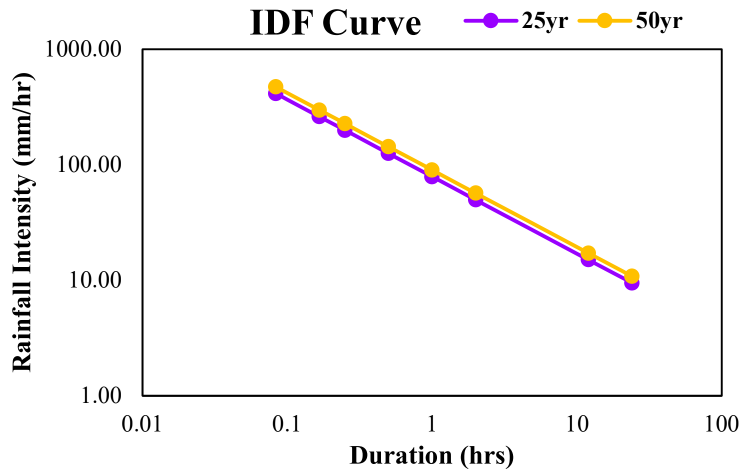

Figure 6: Log paper intensity duration frequency curve

4.2. Time of Concertation and rainfall intensity

Table 4 presents the concentration time determined in the current study using the Kirpich Equation. The results indicate that water flow within the terrain takes approximately 51.287 minutes to reach the outlet. It was observed that when the slope of the channel is increased while keeping the terrain length constant, the concentration time decreases. This is due to the terrain having a milder slope, causing water flow within the terrain to require more time to reach the outlet. Table 4 also presents the rainfall intensity for different return periods. The results show that rainfall intensity increased with increase in return periods. By increasing the rainfall intensity, the concentration time will decrease.

4.3. Runoff coefficient

The runoff coefficient is presented in Table 4, with results indicating that forest and pastureland exhibit smaller runoff coefficients compared to the build-up area. This difference arises from the absence of infiltration in built-up areas, while in forest and pastureland, rainfall is intercepted due to the presence of a vegetated layer. Under a constant slope of the terrain, the runoff coefficient is influenced by the presence of vegetation, which intercepts rainwater and subsequently reduces the overall runoff coefficient.

Table 4: Result of present study and catchment characteristics.

Time of Concentration (min)				
T_c (min)	51.28703132			
Average Intensity (mm/hr.)				
Return Period	**Average Intensity (mm/hr.)**			
Q_{25}	86.55314648			
Q_{50}	98.78766355			
Weighted equivalent runoff coefficient C_e				
Class name	**Areas (km^2)**	**Slope (%)**	**Soil Group**	**C**
Forest Land	4.76	20.307	D (Clay)	0.6

Built-up Area	5.54	20.307	D (Clay)	0.7
Pastureland	8.97	20.307	D (Clay)	0.6
C_e = 0.628749351				
Peak Discharge (m^3/sec)				
Return Period	**Peak Discharge (m^3/sec)**			
Q_{25}	291.238956			
Q_{50}	332.4063558			

5 CONCLUSIONS

The present study has the following conclusion.

- The study concluded that, time of concertation depends on the length and slope of the terrain. The minimum time of concertation noticed was 51.287 minutes.
- The average rainfall intensity was determined for different return periods; it was found to be 86.55 for a 25-year return period and 98.78 for a 50-year return period. This indicates that rainfall intensity increases with an increase in return periods.
- The maximum value of runoff coefficient was noticed for built up area in sector E-11 Islamabad. This was because of no vegetated layer in built-up area. The maximum value of runoff coefficient was 0.7 for built up area.
- The Rational Formula application provides a great starting point for calculating peak floods in partially urbanized catchments, making it a realistic and accessible tool for flood risk assessment.
- Continued research and developments in hydrological modeling will be critical in tackling the growing issues posed by urbanization and climate change as we attempt to construct resilient and sustainable communities.

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