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Development of Intensity-Duration-Frequency Curves for Intake Structures in Irrigation Projects

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Abstract:

Accurately estimating design rainfall intensities is of paramount importance for the effective design and management of water infrastructure. Rainfall Intensity–Duration–Frequency (IDF) relationships are crucial in water infrastructure design and construction. These relationships portray the interplay between rainfall intensity, duration, and frequency, serving as fundamental tools for rainfall analysis, flood management, and infrastructure design. This study focuses on a case study of creating IDF curves for the Toneipal area in Odisha, India, employing Gumbel's distribution and Isopluvial methods. The development of IDF curves involved using daily rainfall data spanning 35 years (1988 – 2022). Historical rainfall data obtained from nearby meteorological stations were meticulously analyzed. Gumbel distribution was employed to establish IDF curves for various return periods extrapolated from the daily rainfall data. Additionally, IDF curves were crafted using Isopluvial maps for the designated region. The results were compared to ascertain the reliability of both methodologies. The Isopluvial method yielded a rainfall intensity 10.6 mm/h higher than the Gumbel method for a 2-year return period. Likewise, for the 100-year return period, the Isopluvial method exhibited a rainfall intensity 4.02 mm/h greater than the Gumbel method. Particularly for shorter durations, the Isopluvial approach indicated higher rainfall intensity. These outcomes underscore the significance of identifying the most fitting distribution that accurately captures observed data for specific rainfall stations. Findings from this study hold significant implications for flood risk assessment and infrastructure planning in Odisha. By shedding light on the variations between different methods of generating IDF curves, the study aids in making informed decisions to enhance flood resilience and ensure robust infrastructure development.

Keywords: IDF curves, Gumbel distribution, Isopluvial method, rainfall intensity, water infrastructure design.

1. Introduction

The precipitation varies significantly between the years, making it challenging for water resources management and water infrastructure design (Kareem et al., 2022). Design rainfall intensities are instrumental in ensuring the resilience and safety of water-related structures and systems. Rainfall intensity analyses, especially intensity–duration–frequency (IDF) curves for the different return periods, are necessary for most water engineering projects. IDF curves encapsulate the probabilistic relationships between rainfall intensity, duration, and frequency of occurrence, thus guiding the planning and design process (Al-Amri & Subyani, 2017; Chow et al., 1988). The accurate estimation of IDF curves has far-reaching implications, influencing the design of urban drainage systems, floodplain management, and water resource planning. IDF relationships are crucial for flood mitigation measures, water engineering projects, and water resources engineering designs (Thanh & Xuan, 2023; Benny & Brema, 2019). IDF curves are used extensively by civil engineers to design and size safely and economically drainage networks of a city or flood control structures. Thus, they are critical for preventing flooding and, as a result, minimising the loss of life and property and the cost of water damage insurance and weather-related risk assessments (Hatem et al., 2017).

The foundation of IDF curves lies in the analysis of historical rainfall data. By scrutinising the statistical distribution of recorded rainfall intensities over various durations, these curves provide insights into the behaviour of extreme rainfall events (Suchithra & Agarwal, 2020). This process allows hydrologists to identify patterns, estimate parameters, and derive relationships between intensity, duration, and return period (Iliopoulou et al., 2022). Through meticulous data collection, quality control, and statistical analysis, accurate IDF curves are developed, serving as essential references for engineering practice.

The Gumbel distribution method, rooted in extreme value theory, provides a robust framework for deriving IDF curves. Assuming that maximum rainfall intensities follow a Gumbel distribution, this method employs statistical techniques to estimate distribution parameters. These parameters enable the construction of IDF curves for diverse return periods and durations (Mahdi & Mohamedmeki, 2020). The Gumbel approach is efficient in regions with substantial historical data and offers a systematic way to estimate design rainfall intensities (ASCE, 2016; Chow et al., 1988).

In situations with limited or spatially heterogeneous data, the Isopluvial method emerges as a valuable alternative. By utilising isopluvial maps, hydrologists can visualise and interpolate uniform precipitation depths across various durations and return periods. This spatial approach overcomes the challenges of sparse data, enabling intensity estimation at ungauged locations (CPHEEO, 2019). The Isopluvial method's ability to provide a comprehensive spatial representation of design rainfall intensities adds a crucial dimension to hydrological modelling and infrastructure planning (Burn & Simonovic, 2001).

The choice between the Gumbel distribution and Isopluvial methods is contingent upon several factors. Data availability remains critical; the Gumbel method thrives when extensive historical data is accessible, ensuring robust parameter estimation. On the other hand, the Isopluvial method accommodates situations with limited data, offering a spatially informed estimate. Accuracy and complexity should also influence the

choice, with the Isopluvial method introducing interpolation uncertainties while catering to data gaps (Mendez et al., 2023; Haan et al., 1994).
The precise estimation of IDF curves underpins the design and management of water infrastructure. The Gumbel distribution and Isopluvial methods stand as prominent approaches for this purpose. Both methods possess unique advantages and constraints, making them suitable for different contexts. The selection between these methodologies requires a judicious evaluation of available data, accuracy requirements, and the specific characteristics of the study area, ensuring a robust foundation for water-related projects. The main objective of this study was to develop IDF curves for the Toniepal region using Gumbel's distribution method from the observed daily rainfall data. Additionally, IDF curves were developed from Isopluvial maps using Empirical equations and the results were compared. In particular, this study's findings could help improve water resource management in local urban areas and the design and operation of stormwater management systems.

2. Study Area

Toneipal is located in Anandapur Tehsil, Kendujhar District of Odisha State, India between 21°20'31" - 21°22'20" N and 86°2'33" - 86°4'20" E (Figure 1). It is located 83 km East of the District headquarters Kendujhar—134 km from the State capital, Bhubaneswar. The physical attributes of Toniepal encompass a diverse range of features. The region's topography significantly shapes its microenvironment, from rolling hills to fertile valleys. Additionally, Toniepal might be influenced by nearby water bodies, such as rivers or streams, which contribute to its hydrological network and broader ecological dynamics. River Baitarani flows within 100 m from the study area. Anandapur typically receives about 129.48 mm of precipitation and has 132 rainy days (36.19% of the time) and the annual average temperature is 30.33°C.

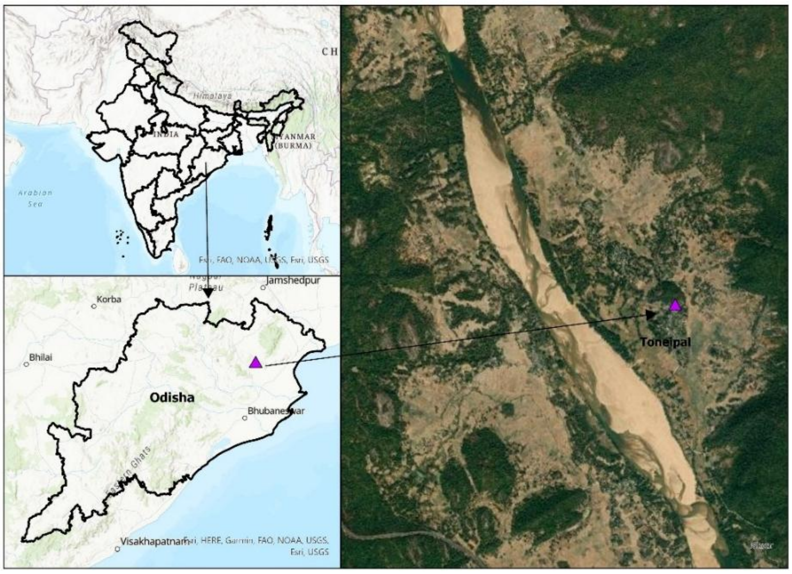

Figure 1: Index map of the Study area

3. Methodology

3.1 IDF Curves using the Gumbel's distribution

Based on the proximity to the Toniepal region, the Anandpur rainfall station was selected for this study. Daily rainfall data was collected from the Anandpur rainfall station for 35 years (1988 – 2022). From the daily rainfall data, hourly rainfall data were calculated using IMD's empirical reduction formula. This study uses the following empirical equation to estimate short-duration rainfall.

$$P_t = P_{24}\sqrt[3]{\frac{t}{24}}$$

where,
P_t - Required rainfall depth in mm at t-h duration,
P_{24} - Daily rainfall in mm and
t - Duration of rainfall in h.

The development of IDF curves requires a frequency analysis for each set of annual maxima, one associated with each rainfall duration. Frequency analysis can be done by fitting a theoretical Extreme Value (EV) distribution to the observations and then using the theoretical distribution to estimate the rainfall events associated with given exceedance probabilities. Several probability distribution functions can be used to describe extreme value data, such as annual maxima. Gumbel's distribution is mainly used for IDF relationships and is used here to fit probability distribution (Thanh & Xuan, 2023; Benny & Brema, 2019; Fordjour et al., 2019). The Gumbel method is a simple approach that can be applied in extreme events (maximum value or peak rainfalls). The frequency of precipitation X_T (in mm) for each duration with a specified return period T (in years) is given by the following equation:

$$X_T = \overline{X} + K_T S$$

where,
X_T - Rainfall intensity at given return period,
X - Mean of time,
S - Standard deviation and
K_T - Gumbel Frequency factor, which is given by the following equation:

$$K_T = -\frac{\sqrt{6}}{\pi}\left\{0.5772 + \ln\left[\ln\left(\frac{T}{T-1}\right)\right]\right\}$$

3.2 IDF Curves using the Isopluvial Method

The Isopluvial or isohyetal method estimates design rainfall intensities across a region with limited rainfall data. It involves the creation of isopluvial maps that depict regions with uniform rainfall depths for specific durations and return periods. These maps allow for spatial interpolation of rainfall intensities at ungauged locations. The Isopluvial method remains a valuable option in areas with limited data.

IMD is supplying an atlas of state-wise generalized isopluvial maps of 24-h rainfall of different return periods, viz., 2-yr, 5-year, 10-year, 25-year, 50-year and 100-year, so that design engineers can estimate design flood according to their requirement. The daily rainfall data obtained from Ordinary Rain gauges (ORG) at 746 stations inside the states, and in their neighbourhood, having data for more than 30 years and in the case of some stations, ORG data of even more than 100 years has been utilized to provide the Isopluvial maps (Das et al., 2022).

IDF relationship formulae are empirical ones developed based on the observation that as a storm's duration increases, the storm's intensity decreases. Bernard equation is generally adopted for Indian conditions.

$$i = \frac{a}{t^n}$$

where,

i - Intensity of rainfall (mm/h.),

t - Duration of rainfall (minutes) and

a, n – Constants

4. Results and Discussion

Rainfall analysis for 35 years, from 1988 to 2022, is considered in this study. Anandpur rainfall station is considered the influencing rain gauge station for the study area. The Annual Daily Maximum Rainfall ranges from 28mm to 415mm. The highest daily rainfall was recorded in 1999 and the lowest in 1994. The Annual Daily Maximum Rainfall for each year is estimated from the daily rainfall data (Figure 2).

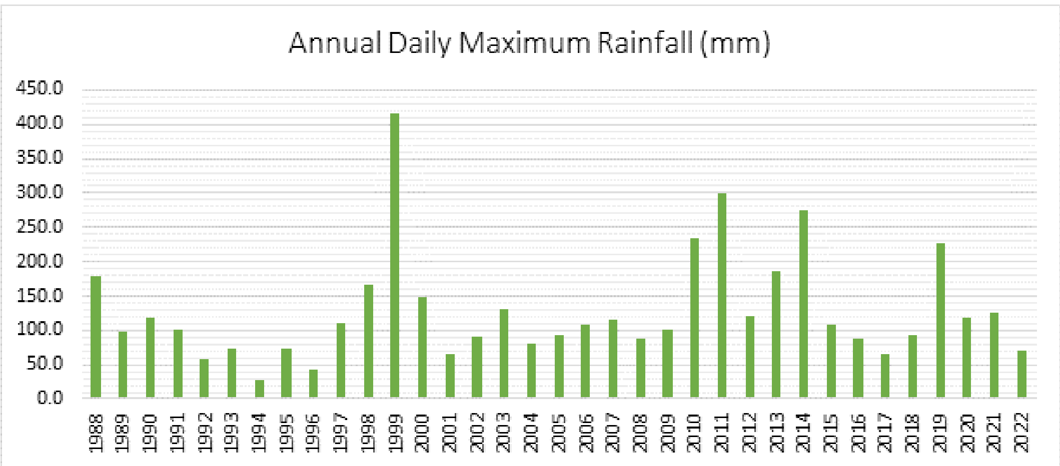

Figure 2: Annual Maximum Daily Rainfall values for each year at Anandpur rainfall station

Hourly rainfalls of various durations like 1h, 2h, 3h, 6h, 12h, 18h and 24h rainfall values were calculated from annual maximum values. The mean and standard deviation for the data for different durations is calculated (Table 1).

Table 1: Mean and Standard deviation derived using the observed rainfall data.

Duration (h)	**1**	**2**	**3**	**6**	**12**	**18**	**24**
Mean	38.79	24.44	18.65	11.75	7.40	5.65	4.66
STD.DEV	15.87	10.00	7.63	4.81	3.03	2.31	1.91

The frequency factor, K_T values are calculated for 2, 5, 10, 50 and 100-year return periods using Gumbel's distribution is shown in Table 2.

Table 2: Values of Frequency factor for different return periods

Return period (years)	**2**	**5**	**10**	**50**	**100**
Frequency factor K_T	-0.164	0.719	1.305	2.592	3.137

Table 3. presents maximum rainfall intensities at durations of 1h, 2h, 3h, 6h, 12h, 18h and 24h at return periods of 2, 5, 10, 50, and 100 years.

Table 3: Rainfall intensities for different durations and return periods derived by Gumbel's method.

Duration (h)	**Rainfall intensities (mm/h)**				
	2 Year	**5 Year**	**10 Year**	**50 Year**	**100 Year**
1	40.05	64.39	80.54	116.02	131.04
2	25.23	40.56	50.74	73.09	82.55
3	19.25	30.95	38.72	55.77	63.00
6	12.13	19.50	24.39	35.14	39.69
12	7.64	12.28	15.37	22.13	25.00
18	5.83	9.37	11.73	16.89	19.08
24	4.81	7.74	9.68	13.94	15.75

The rainfall intensities for 1-h duration are 40.05, 64.39, 80.54, 116.02 and 131.04 mm/h for 2, 5, 10, 50, and 100 years return period respectively. The rainfall intensities for 24-h duration are 4.81, 7.74, 9.68, 13.94 and 15.75 mm/h for 2, 5, 10, 50, and 100-year return periods respectively. The IDF curves for Toniepal derived using the Gumbel method are shown in Figure 3.

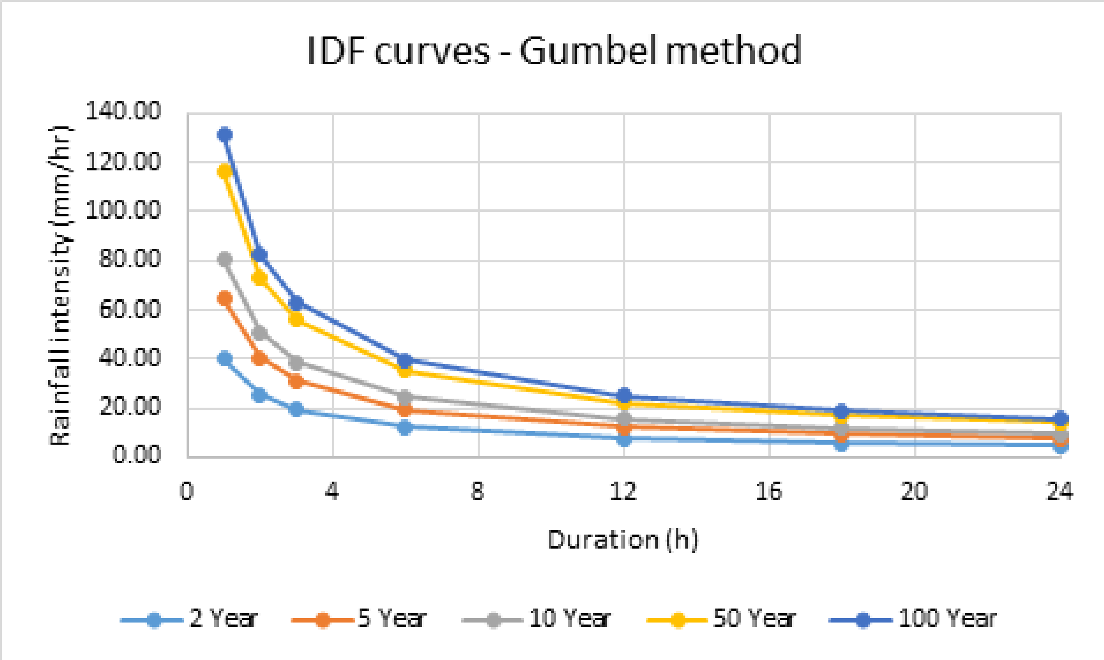

Figure 3: IDF curves developed for return periods of 2, 5, 10, 50 and 100-year using the Gumbel method.

Isopluvial-based approaches offer more precise spatial estimates of design rainfall intensities, making them indispensable in data-scarce regions. The information from spatial distribution maps estimates the IDF curve parameters at ungauged locations. For specified return periods and durations, extract the interpolated design rainfall intensities from the isopluvial maps (Table 4).

Table 4: Rainfall intensities for different durations and return periods derived by the Isopluvial method.

Duration (h)	**Rainfall intensities (mm/h)**				
	2 Year	**5 Year**	**10 Year**	**50 Year**	**100 Year**
1	50.65	67.53	84.41	118.18	135.06
2	30.81	41.08	51.35	71.90	82.17
3	23.04	30.72	38.40	53.76	61.44
6	14.02	18.69	23.36	32.70	37.38
12	8.53	11.37	14.21	19.90	22.74
18	6.38	8.50	10.63	14.88	17.00
24	5.19	6.92	8.65	12.10	13.83

The rainfall intensities for 1-h duration are 50.65, 67.53, 84.41, 118.18 and 135.06 mm/h for 2, 5, 10, 50, and 100-year return periods respectively. The rainfall intensities for 24-h duration are 5.19,6.92, 8.65, 12.10 and 13.83 mm/h for 2, 5, 10, 50, and 100-

year return periods respectively. A graph of the estimated design rainfall intensities against the corresponding durations is shown in Figure 5.

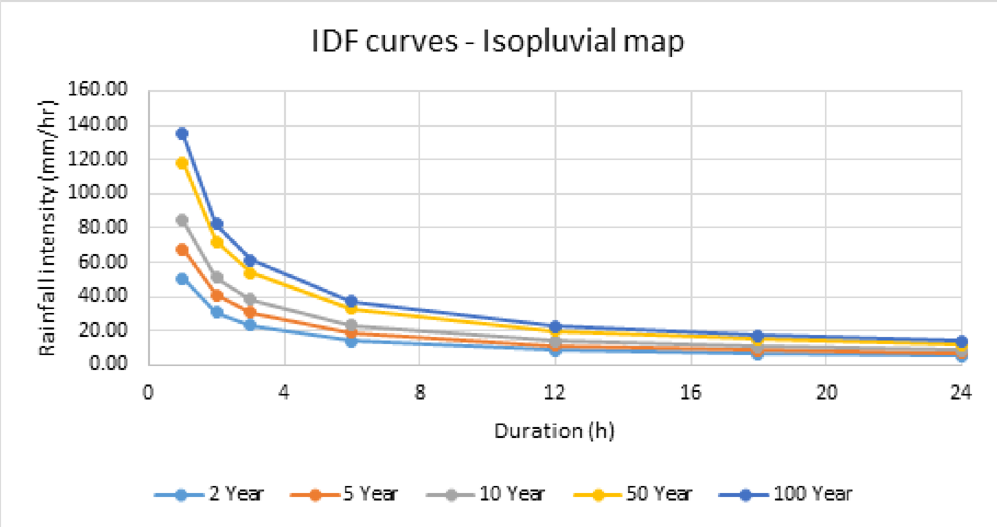

Figure 5: IDF curves were developed for return periods of 2, 5, 10, 50, and 100 years using an Isopluvial map.

While comparing, the results showed that the values obtained from the Gumbel distribution and the Isopluvial method have slight deviations for longer durations. However, for shorter durations, the rainfall intensities derived using the Isopluvial map are higher than those derived from Gumbel's distribution. The difference in rainfall intensities between the Gumbel method and the Isopluvial map is shown in Table 5. Positive values indicate the extent to which rainfall intensities, as depicted by Isopluvial maps, surpass those obtained through the Gumbel method. At the same time, negative values indicate the decrease in rainfall intensity by the Isopluvial map compared with the Gumbel method.

Table 5: Difference in rainfall intensities between the Isopluvial map and the Gumbel method

Duration (h)	Rainfall intensities (mm/h)				
	2 Year	5 Year	10 Year	50 Year	100 Year
1	10.60	3.14	3.87	2.16	4.02
2	5.59	0.52	0.62	-1.19	-0.38
3	3.79	-0.24	-0.32	-2.02	-1.56
6	1.89	-0.81	-1.03	-2.43	-2.31
12	0.89	-0.92	-1.15	-2.24	-2.26
18	0.55	-0.87	-1.10	-2.01	-2.08
24	0.37	-0.82	-1.03	-1.84	-1.92

The Gumbel distribution method relies on extreme value statistics and distribution parameters, while the Isopluvial method leverages spatial mapping and interpolation techniques. The Gumbel distribution method involves calculating return values using parameters estimated from the historical data, while the Isopluvial method uses spatially interpolated values from isohyetal lines and maps to estimate design intensities. The selection of the appropriate method depends on data availability, accuracy needs, and the spatial characteristics of the study area (ASCE, 2016; Chow et al., 1988). The choice between these methodologies should be made carefully, considering factors such as the availability of high-quality data, the sophistication of statistical and geospatial tools, and the specific nature of the study area. While the Gumbel distribution method offers precise insights into extreme rainfall quantification, the Isopluvial method provides a spatial dimension to design rainfall intensity estimation, especially in regions with data limitations (Burn & Simonovic, 2001; Haan et al., 1994).

5. Conclusion

In this study, IDF curves were derived for rainfall durations 1h, 2h, 3h, 6h, 12h, 18h and 24h at return periods of 2, 5, 10, 50, and 100-years for Toniepal region in Odissa, India. The IDF curves were compared between Gumbel's distribution of observed data and the Isopluvial method. The rainfall intensities for 1-h duration using the Gumbel method are 40.05, 64.39, 80.54, 116.02 and 131.04 mm/h for 2, 5, 10, 50, and 100-year return periods respectively. The rainfall intensities for 1-h duration using the Isopluvial method are 50.65, 67.53, 84.41, 118.18 and 135.06 mm/h for 2, 5, 10, 50, and 100-year return periods respectively. For a 2-year return period, the Isopluvial method's rainfall intensity is 10.6 mm/h higher than the Gumbel method. For the 100-year return period, the Isopluvial method's rainfall intensity is 4.02 mm/h higher than the Gumbel method. Thus, the difference in rainfall intensity decreases with an increase in return period and duration. Rainfall intensity for a shorter duration is higher in the Isopluvial method. Therefore, Isopluvial method can be adopted for longer duration and higher return periods if there are any data limitations. But for a shorter duration, the Isopluvial method estimates higher rainfall intensity which is not optimum for design. These results also reinforce the need to detect the most suitable distribution that best fits observed data for a particular rainfall station, especially when time series are asymmetric or extreme values are present. Likewise, as return periods get longer, deviations between rainfall estimates obtained with the different probability distributions are more accentuated.

The rainfall intensities obtained for different durations can be used to calculate the flood hydrographs for different design floods. The floods with higher return periods were severe compared to those with lower return periods. The rainfall IDF curves for extreme rainfall play a vital role for design engineers, hydrologists, and hydraulic consultants of different public and private sector organizations for planning and designing water resources-related projects, viz., construction of small hydraulic structures, planning of irrigation drainage purposes, airports, power plants, railways, metro rail, road bridges, National Highways, culverts etc. A short duration of high-intensity rainfall may cause disastrous consequences in an area if a proper drainage system is unavailable. This study of IDF curves will help take future courses of action for constructing drainage systems and planning for water management.

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